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Case Study Assessment of 3D and 4D Modeling Techniques for Early Constructabilty Review of Transportation Projects

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Case Study Assessment of 3D and 4D Modeling Techniques for Early Constructabilty Review of Transportation Projects

by

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Dedication

To my wife Morgan who has always supported me in everything I do, and my beloved family.

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Thank you to Duane Milligan and Jeff Bush for their help on the case study projects.

Abstract

Case Study Assessment of 3D and 4D Modeling Techniques for Early Constructabilty Review of Transportation Projects

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Transportation projects are unique projects that have many issues such as ROW acquisition, traffic control, and utilities. To help solve some of these issues projects should utilize constructability. Over the past 25 years research on constructability has consistently shown to have substantial cost and schedule benefits. To fully obtain those benefits, constructability should be utilized from the very beginning of the project at the conceptual planning phase. One of the tools to support implementation is 3D and 4D visualization. The benefits and applications of 3D and 4D for transportation project research is still lagging behind building projects. This thesis aims to provide a frame work for how 3D and 4D visualization could have an impactful role if used in the early planning and design process. Two case studies are used for developing that frame work, the Woodall Rodgers Deck Plaza and the Eastern Extension of President George Bush Turnpike projects in Dallas, Texas. Information taken from interviews of Texas Department of Transportation staff are used to develop a list of issues for each project, as well as the impacts those issues have had on the project. For each of those issues a proposal of how using 3D and 4D visualization could help mitigate those issues when implemented during the early planning phases.

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Chapter 1: Introduction

This thesis reviews constructability for transportation projects. More specifically, the use of 3D/4D CAD as a tool for constructability implementation. Constructability has proven benefits from 25 years of research and benchmarking by the Construction Industry Institute (CII). CII has cited cost reduction between 6 and 23 percent with benefit/cost ratios of up to 10 to 1 from implementing constructability. That is considerable savings for projects if constructability is implemented effectively.

A tool that can assist with implementation is 3D/4D CAD. While there is a large amount of research on the benefits of 3D/4D CAD for buildings, the benefits to transportation projects have not been as thoroughly research, and thus not as fully developed and proven as for buildings. In order to build the benefits and applications of 3D/4D CAD for transportation, research should look at the areas where building research has proven benefits. The analysis conducted for this thesis utilizes some of the benefits that have been proven on building projects.

The analysis was done for two project case studies in Dallas, the President George Bush Turnpike (PGBT) and Woodall Rodgers Deck Plaza. Most of the analysis was completed during the construction phase of the project. The analysis was beneficial for the projects, but several of the issues could have potentially not become issues by using 3D and 4D modeling during the early planning and design phases. This thesis presents a possible framework of how several of the issues encountered during construction could have been solved or improved by utilizing 3D and 4D modeling early in the project phases.

1.1 Readers Guide

This thesis contains four chapters. The present chapter introduces the topic and provides some brief context of why that topic is important. Chapter 2 of this thesis reviews previous work conducted on constructability as well as 3D/4D CAD for buildings and transportation projects to provide a framework for this research. Also included at the end of Chapter 2 is a section on the research questions this thesis aims to answer. Chapter 3 presents the two case studies, PGBT and Woodall Rodgers. For each case study the analysis conducted for TxDOT is discussed, the issues from interviews with the project manager are presented, and for each of the issues discovered a potential frame work is presented about how utilizing 3D/4D during the early planning and design phases could have potentially eliminated the issue or at least reduced its impact. Chapter 4 covers conclusions from the research and also provides some recommendation for future work on the topic.

Chapter 2: Literature Review

2.1 Constructability

2.1.1 Need for Constructability/Transportation Challenges

Transportation projects are very different from other projects such as buildings or industrial plants. These differences create several unique issues that need to be addressed in order to have a successful project. Goodrum et al. (2003) conducted a survey of both employees with the Kentucky Transportation Cabinet and highway contractors. The top three challenges they identified were utilities, traffic control, and right of way (ROW). Note: Geotechnical concerns were actually the third issue, but the authors (Goodrum et al.) thought there might be a biased due to the people being surveyed being from Kentucky with unique Karst Geology.

Utilities such as water, sewer, drainage, electricity, gas, and communication networks are run on transportation right of ways (ROW). When expanding a road, the utilities that are on the ROW must be relocated; this can create several issues (Chong et al. 2005; Ellis and Thomas 2002). As an indication regarding the frequency of utility conflicts, a report by the United States General Accounting Office (USGAO 1999) showed that 22 out of the 44 states surveyed in the research reported utility delays on at least 11% of the projects within their state. The USGAO report further indicated that this estimate may be low, since many State Transportation Agencies (STAs) acknowledge that utility delays often occur on their roadway projects without their knowledge. Specific issues regarding utilities are listed below (Hugo et al., 1999).

1. Trouble locating existing utilities before construction begins;
2. Construction delays due to utility relocation;
3. Unforeseen existing utilities that interfere with proposed construction;
4. Utilities relocated incorrectly
5. Existing utilities in locations other than shown on plans.

Traffic control is needed to divert and control traffic while simultaneously building a project (Goodrum, 2003, Russell and Swiggum, 1994; Hugo et al., 1990, Liapi et al., 2003). This is a major issue because “most current highway projects involve rebuilding and/or expanding existing roadway" (Goodrum et al., 2003). To further complicate things, state transportation agencies (STA) make promises to the public to "minimize disruptions to traffic flows and reduce congestion due to construction activities" (Goodrum et al., 2003). The STAs, by trying to keep traffic flowing as normal as possible, are creating a trade off by making construction projects more complicated to complete.

Right of way issues happen because the design team works backwards in comparison to other types of projects. Rather than design a project based on land purchased, transportation projects purchase land based on a design they have created. The issues created include the following from Goodrum et al. (2003)

1. Right-of-way agreements not secured prior to construction thus causing delays
2. Differences between what was agreed to between land owners and the agency in right-of-way agreements and what is shown on plans
3. Plans having not enough detail during right-of-way negotiations
4. Not enough space in right-of-ways for construction activities
5. Schedule of securing right-of-way agreements not coinciding with the project's construction schedule

Another one of the biggest differences between transportation projects and most other projects is the site conditions. For transportation projects, all of the work and workers are exposed to the elements (cold, rain, snow, sun, etc) (Hugo et al., 1990; Kim et al., 2011). Also, often large area transportation projects encompasses and can create different topographies for the same project (Hugo et al., 1990; Kim et al., 2011). The large area also creates logistic issues with communication and transportation within the project boundaries. These site condition factors add complexity to design as well as construction. Designing project components and systems to be exposed to constantly changing weather or underground issues is more challenging than if they were protected, as in a building.

STAs are public entities which mean there are very strict guidelines and increased restrictions that must be followed for construction projects. This "public accountability limitation" creates additional challenges for completing transportation projects (Hugo et al., 1990). One of the guidelines is that, barring any special circumstances, the lowest bidder for the project is awarded the job; not the most qualified. The most qualified bidder may not have been the low bidder, because they saw issues others did not. Those issues, if not realized in the bidding phase, could, and often do, cause issues later when construction has started.

While there are a lot of unique aspects to transportation projects, there are also challenges all construction projects face that constructability can address. It has always been the goal of STAs to lower project costs so they get the most benefit for the public, but due to the somewhat recent economic downturn the amount of funding for transportation projects has been reduced from levels in the past. According to a congressional commission the funding gap between the country's transportation needs and currently available revenue sources is about $137,000,000,000 annually. This information is even more of a reason to try and lower projects costs. Delivering projects on time is another goal for all construction projects, but the increased demand on roads is another driving force to deliver projects on time or early. The earlier the project is done, the earlier traffic can return to normal.

According to Kim et al. (2011), Constructability can help to address these issues. "Constructability oriented planning at the preconstruction or construction phase is essential to overcome inefficiency of project management" (Kim et al., 2011).

2.1.2 Constructability Definition, History, and Benefits

The most widely accepted and used definition is provided by the Construction Industry Institute. Constructability is:

"The optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives." (CII 1986)

CII has been studying constructability for approximately 25 years (almost as long as it has existed). CII grew out of the Business Roundtable's efforts to "motivate the construction industry to improve its work methods and cost effectiveness" (Business Roundtable, 1983). The Business Round table published a series of studies in 1983 that lead to the word "constructability" being used in the collective vocabulary of the U.S. construction industry (Pocock et al., 2006).

The benefits accumulated over the past 25 years from implementing constructability reviews provides great assurance that these reviews can address issues with transportation projects. Pocock et al. (2006) surveyed approximately 100 owners, architects, engineers, consultants, contractors and construction managers from across the United States. The survey offered six possible benefits of implementing constructability. The responses are listed below in ranked order along with the percentages. According to Pocock et al. (2006), "all the benefits received very strong support… and the respondents clearly see a wide range of good reasons for implementing constructability".

1. Minimizes contract changes orders and disputes (89%)
2. Reduces project cost (82%)
3. Enhances project quality (81%)
4. Reduces project duration (70%)
5. Increases owner satisfaction (60%)
6. Enhances partnering and trust among project team (58%)

Some of those benefits (change orders, costs, and duration) are quantifiable and the others are intangible. CII research has cited cost reduction between 6 and 23 percent with benefit/cost ratios of up to 10 to 1. Hugo et al. (1990) also cites "that constructability affords the opportunity…for achieving greater efficiency, with resulting lower costs, reduced schedule, or improved quality."

Intangible benefits are not quantifiable are still very important. According to Tatum (1987) "there are many benefits for which reduction to dollars saved is not possible. Among these, team building, improved coordination of design and construction, greater construction planning, and adoption of a project viewpoint by all team members". CII (2006) also mentions "more accurate budgets, improved site layout, improved project team relationships, more repeat work, and improved security".

2.1.3 Constructability Implementation – Concepts, Timing, and Tools

The full benefits of constructability can only be realized when it is implemented holistically. This means focusing on the overall project objectives, implementing it during all project phases, ensuring all project players are in support, and utilizing all the tools possible (CII, 2006).

CII (2006) developed a list of constructability concepts to assist implementing constructability. This was done because construction projects are unique and a single list of instructions or check list would not produce the full benefits of constructability. The concepts provide generalized thoughts about how to implement constructability, while the project team fills in the details that are specific to their project. For instance, concept II-3 is that "design elements are standardized" (CII, 2006). This provides the constructability team with a starting point that they need to look at what parts of their specific project design can be standardized. The concepts helps to focus the team's constructability efforts.

Focusing on the overall project objectives means looking at the big, overall picture, rather than on individual sub-objectives (CII, 2006). For example, a designer that attempts to minimize design effort only may actually cause an increase in construction effort, which in turn increases the project's overall life-cycle cost (CII, 2006).

Most of the research supports implementing constructability at the beginning of the project. CII (1986) states "maximum benefits occur when people with construction knowledge and experience become involved at the very beginning of a project." This is because "decisions made early in the project, despite the low levels of expenditure at that time, have the highest influence on total cost", which can be seen in Figure 2-1(Tatum, 1987).

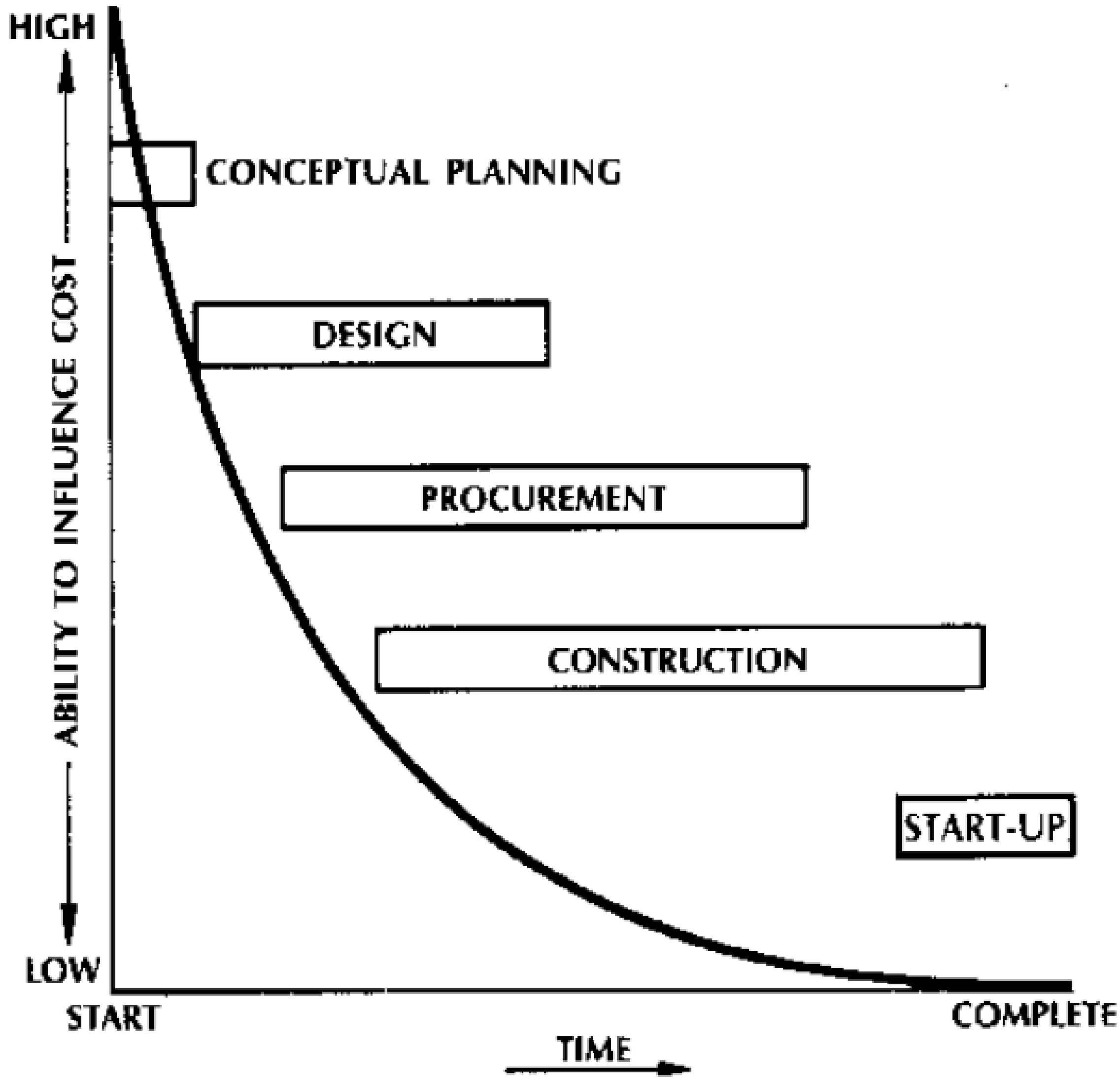

Figure 2-1 Ability to influence final cost over project life (CII, 1986)

While constructability should start early, it should also continue throughout the project life-cycle. Even during construction, constructability issues still exist. Thus, constructors can still reap constructability benefits from their actions alone (O'Connor and Davis, 1988). This is graphically depicted in Figure 2-2 in which the ability to influence final project cost during field operations is still considered significant, albeit substantially less significant than during the prior phases of procurement, design, and conceptual planning (O'Connor and Davis, 1988).

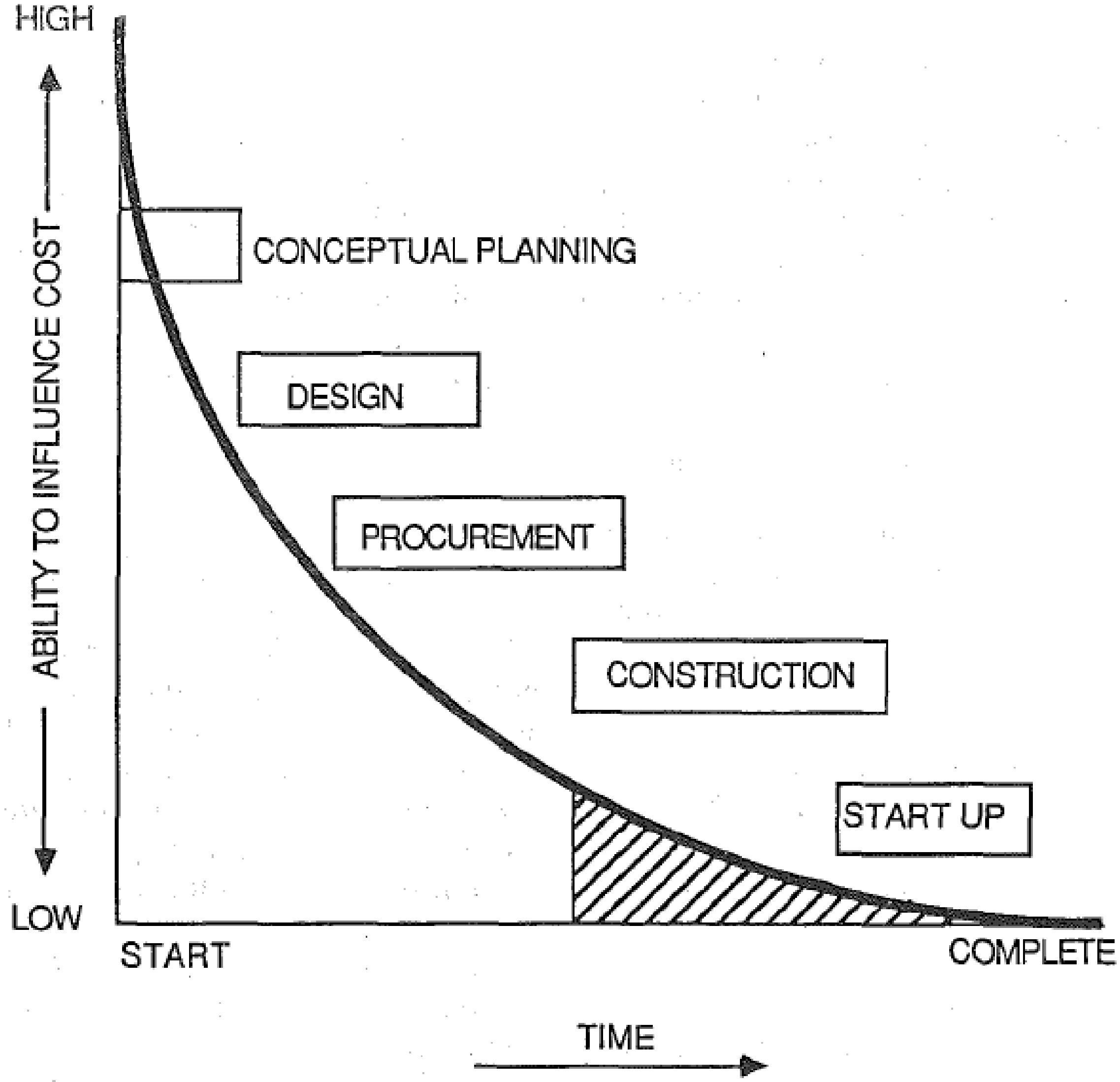

Figure 2-2 Ability to influence final cost during construction (CII, 1986)

Implementing constructability can be challenging. Several tools over the years have been created to help implement constructability more holistically on projects. According to Anderson et al. (1999), "Tools are provided to help communicate and understand constructibility and to implement and measure constructibility. They can be either paper-based (i.e., checklists, policy statements, etc.) or computing tools (i.e., expert systems, process modelers) that facilitate ease of implementation." Several paper based tools can be found in an implementation guide CII developed in order to help more companies and projects implement constructability (CII, 2006). The guide provides a roadmap that "provides guidance in the planning, development, and implementation of constructability programs" (CII, 2006). The guide also provides the following other paper-based documents:

- Program evaluation matrix
- Barriers assessment checklists
- Barrier breakers list
- Sample program documents
    - Implementation policy(Fisher et al., 2000)
    - Organization chart (Fisher et al., 2000)
    - Planning workshop agenda
    - Suggestion form (Fisher et al., 2000)
    - Idea log
    - Contract clauses (Fisher et al., 2000)

McManus et al. (1996) and AASHTO (2000) echo the use of checklists commenting "checklists do not need to stringently adhered to but should serve as a means for the reviewers to focus on areas and issues of concern" (AASHTO, 2000). Pocock et al.'s (2006) survey listed checklists as the fourth most used mechanism for constructability implementation with 29% of respondents utilizing it.

Fisher et al. (2000) suggest people can be tools as well. Pocock et al.'s (2006) survey about "what mechanisms are most commonly used to address constructability on your projects". The top three responses were people based tools. Results with the percentage of companies using them indicated are presented below.

1. Review by expert (57%)
2. Peer reviews (49%)
3. Expert on design team (33)

Reviews by experts popularity is echoed by several other authors as well. Mendelsohn (1997) thought "a construction expertise must be brought in before any design is put to paper." AASHTO (2000) commented that "contractors, when given the option, will most likely find the most economical method of building a project. If we [project owners] can take advantage of this in the design stages, then we can provide the highest quality project at the most economical cost." Ninety-five percent of 134 design firms Arditi et al. (2002) surveyed "are of the opinion that construction engineers should be involved in the design phase."

Another person tools presented in the literature is the use of a constructability champion. CII (2006) recommends appointing a champion as one of the major steps in the implementation road map. AASHTO (2000) also comments that "all successful STA programs have established champions" that "provide leadership and corporate commitment to the process."

Technology based tools are also very helpful for implementing a constructability program. Fisher and Rajan, (1996) developed an automated system - TRAPS to "aid traffic engineers, construction managers, and other highway design personnel in the analysis of traffic-control planning and scheduling." More specifically, it "helps in the appropriate staging and phasing of the TCP, and also calculates the fuzzy duration period of each activity in the TCP. Finally, it links to the project-management software, Microsoft Project, to perform the scheduling of the project and to generate Gantt charts" (Fisher and Rajan, 1996). TxDOT's evaluation stated they were "satisfied with the results of the research and expressed interest in extending the research" (Fisher and Rajan, 1996).

2.2 3D and 4D Models

2.2.1 Introduction

Construction projects have traditionally relied on two dimensional (2D) ways of communicating design when humans live in a three dimensional (3D) world (Carvajal, 2005). When projects are communicated with only two dimensions there is a significant amount of human "brain power" that has to connect the numerous overlapping 2D forms of communication (Koo and Fischer, 2000). Resources that can alleviate some of the information the brain is storing and computing would allow for other high level thinking a computer cannot do. One of those resources is the, somewhat recent, development of 3D and 4D computer visualization models. The computer visualization models are able to take the, sometimes thousands of, 2D documents and synthesize them into 3D and 4D model on the computer. Three dimensions, meaning all of the spatial dimensions (x,y,z) and the fourth typically being time.

In addition to synthesizing large amounts of information into one platform, 3D and 4D models allow for project teams to preview or simulate the work they will be doing before committing large amounts of resources (money, time, personnel). According to Kim et al., (2011) "analyzing an operation in the office, as compared to improvising the same operation on-site, substantially reduces costs." Also, as computers have become more powerful during the past 10 years, 3D and 4D models have become more prevalent in construction. (Kim et al., 2011; Easa et al., 2002). Recently Park et al. (2011) used a focus group interview with 8 participants whom have an average of 19 years experience in the construction industry to identify "35 application areas where visualization, communication, and numerical calculation capabilities of 3D/4D CAD were emphasized." These 35 application areas were then verified to be "important construction processes" and that "3D/4D CAD was considered applicable" for those processes by 165 engineers in the construction industry with an average of 11.3 years of experience. The large number of applications and validation by numerous professionals helps put the, very active, current practice of using 3D and 4D modeling into perspective. One area that has seen a great deal of research is buildings.

2.2.2 3D and 4D CAD for Buildings

Building research has seen such advancement that the most recent building research is not only using 3D and 4D, but is moving towards Building Information Modeling (BIM) which consists of "3D components with additional parameters or attributes and links among the models, components, and information" (Ospina-Alvarado and Castro-Lacouture, 2010). It is an intelligent mode. The benefits extracted from numerous research projects on buildings could also be useful for transportation projects. Therefore 3D and 4D models for buildings are reviewed as a means to find potential benefits for transportation projects.

Koo and Fischer (2000) were some of the first to study the benefits of 3D and 4D CAD for commercial construction projects. They found that 3D and 4D models had three main areas of application; a visualization tool, an integration tool, and analysis tool. A visualization tool conveys planning information, an integration tool "enhances collaboration among project participants", and an analysis tool "supports users to conduct additional analysis." Those three areas are used to organize the different pieces of literature the author reviewed.

2.2.2.1 Visualization Tool

Visualization is an important tool for human understanding, because according to Treichler (1992) "people learn up to 83% of new information through sight". Piagetian theory says that individuals acquire spatial visualization ability through three stages. The first is when children learn topological spatial visualization, i.e. how close the objects are to one another. The second is when people acquire projective representation so they are able to conceive what an object will look like from different perspectives. The final stage of spatial visualization development, a person learns to combine projective abilities with the concept of measurement. This last stage is where a number of people lag behind individuals who, through their careers or daily activities, develop good spatial abilities. For those individuals that lag behind, 3D and 4D models could potentially be a good tool for visualizing a project.

According to Koo and Fischer, (2000), 3D and 4D models "obviate the need to conceptualize the association between components and activities to comprehend the schedule. Also the models show "the spatial constraints between components, enabling users to detect space-related conflicts" (Koo and fisher, 2000). This is very advantageous to communicate design ideas to people who have not developed good spatial abilities such as owners, potential clients, and the public (Gao et al., 2005; Hartmann et al., 2008, Ganah et al. 2005). Below are several applications and benefits of using 3D and 4D models as a visualization tool.

2.2.2.1.1 Bidding

As a visualization tool 3D and 4D models can be used in the bidding phase of a project, to better present the design to bidders. (Gao et al., 2005; Hartmann et al., 2008). One of the cases Gao et al. (2005) studied had a 4D model that was as part of the bid package to visualize problematic design areas or construction sequences. That way potential bidders are better able to fully understand the design and construction work. This resulted in bids closer in proximity to each other with fewer contingencies. All the bids were also within 2% of the owner's estimate. On the opposite side, general contractors (GC) can use 3D and 4D models to help win projects during the proposal stage by "helping the owner to visualize the future and demonstrate that the GC has the best approach for executing the project" (Gao et al., 2005).

2.2.2.1.2 Design Details

Ganah, et al. (2005) proposed using 3D and 4D for "communicating design information related to constructability between design and construction teams." The focus of the case studies was on modeling design details that are very intricate such as "the assembly of cladding, roofs and stairs." They found that "3-D modeling helps in identifying any missing information for building a particular component" and that "by modeling design details [in 3D], decisions can be made on the design and the results can be seen before the construction start."

2.2.2.2 Integration Tool

Integration of all project team members is very important for success on a project. According to Ospina-Alvarado and Castro-Lacouture, (2010), more integration between Architecture, Engineering, Construction, and Facilities Management (AEC+FM) could help overcome issues that are preventing the construction industry from achieving the desired levels of performance in productivity, quality, safety, cost, schedule, and sustainability. Specifically, engineers can use knowledge visualization tools to "improve the transfer of knowledge by enabling the transfer of insights, experiences, attitude, values, perspectives, and opinions between individuals" (Burkhard, 2004).

As an integration tool, 3D and 4D models "facilitate integration processes of all parties involved in the planning process by…formalizing and standardizing the information exchange between project participants and by promoting interaction among them" (Koo and Fischer, 2000). Also, when building the 4D model it encourages interaction between the designer, planner, and builder (Koo and Fischer, 2000). Specific applications are discussed below.

2.2.2.2.1 Constructability Reviews

Hartmann and Fischer (2007) used 3D/4D visualization to support constructability reviews on a major subway reconstruction project in New York City (NYC). The project team in NYC decided to build a 3D/4D model of the project to "support, visually, the communication between numerous stakeholders of the project." The models were used during design review meetings, to generate drawings for communicating design" (Hartmann and Fischer, 2007). With these 3D and 4D models "the project team could communicate product and process knowledge more efficiently". (Hartmann and Fischer, 2007)

2.2.2.2.2 Trade Coordination

The building sector of the construction industry relies heavily on subcontracting work to specialty contractors (Koo and Fisher, 2000). Coordinating their design, all of their work, and establishing clear delineations of work scope, can all be facilitated through 3D and 4D modeling (Gao et al., 2005; Hartmann et al., 2008). Specifically, general contractors use 3D and 4D to coordinate the detail design process by putting together a 3D coordination model that can check the accuracy of the design for interferences of different subcontractors systems (Gao et al., 2005, Hartmann et al., 2008). The 3D model is then used to develop a 4D model to make sure that "the work carried out by different subcontractors do not interfere (Gao et al. 2005). During the construction phase, viewing a 4D model with trade management personnel "elucidated work flow and provided visual justification of the general contractor's work logic" as well as "helped [subcontractors] predict which areas would be congested and enabled the general contractor to coordinate activities" (Gao et al. 2005). On one case RFI's were reduced 80% because of the coordination abilities of the 3D and 4D models (Hartmann et al., 2008). On another case there were no change orders from unexpected design conflicts for mechanical, electrical, and plumbing (MEP) work (Hartmann et al., 2008). Owners can use 4D models to "determine the optimum contractual work packages…and phased handover" (Gao et al., 2005). One of the cases Gao et al. (2005) used, the owner "successfully used the 4D visualization to determine the contracting packages by visualizing the break-up of project scope into various contractual 'chunks' in the 3D model and by seeing progression of the 'chunks' over time in the 4D model" (Gao et al., 2005).

2.2.2.3 Analysis Tool

The ability of 3D and 4D models to contain a large amount of information in a single viewable source creates the ability to do several types of analysis (Koo and Fisher, 2000). In a general sense, the type of analysis that can be done with 3D and 4D models is only limited by the power of computers and human imagination. The practical limitation is the ability for the type of analysis to be cost effective.

2.2.2.3.1 Safety Management

Despite improvements in safety in the construction industry, statistics show that the fatality rate is still relatively high compared to other industries (BLS, 2007). In present day construction, safety is a constant task project management is worried about (Han, et al., 2009). Therefore, to improve safety on the jobsite is a positive. According to Koo and Fisher (2000) "all construction projects are unique in nature and many accidents occur due to unforeseeable human errors, it can be difficult for project managers to anticipate all the hazard areas existing on the site." Viewing "the time and location of work through the 4D model, project managers can perceive how separate crews may affect one another" (Koo and Fisher, 2000). Once the project managers understand potential safety issues or areas, they can prevent them (Han et al., 2009). This can be done by putting up prevention measures such as warning signs, restricting access, or providing safety guards (Koo and Fisher, 2000). The 4D model can also be used directly by showing it to the crews so they better understand how their work relates to others and prevent accidents by anticipating them (Koo and Fisher, 2000, Han et al., 2009). Seeing a video simulation of the situation will be more effective than verbally describing (Han et al., 2009).

2.2.2.3.2 Estimating

For estimating, 3D models are used to generate a bill of quantities as well as directly linked to the estimating software so any updates in the 3D model are automatically updated "through the whole estimating cycle (Staub-French et al., 2003a,b). Using 3D models for estimating purposes saves time while still providing an accurate estimate. According to Hartmann et al. (2008), several case studies used automated quantity take off and reported up to a 25% reduction in overall estimating efforts. One project that tied the 3D model with the estimating software reported an 80% time savings and accuracy within 3% of their detailed estimates (Hartmann et al., 2008).

2.2.2.3.3 Analyzing Design Options

Design engineers can use 3D models as input for design analysis and simulation software applications. The results obtained from the software applications using 3D are usually more accurate than 2D (Augebroe and Hensen, 2004; Bartak et al. 2002; Hong et al. 2000). Kam and Fischer (2002) found a case where a 3D model was used for multiple simulations to predict the interior lighting and energy usage of the building. The 3D model enabled designers to ensure there was enough lighting and the building systems were able to provided comfortable temperatures. Designers were also able to simulate and optimize the operating costs of the building by evaluating three different design alternatives. Gao et al. (2005) studied a case that used 3D models for three design and two life-cycle alternatives, thus creating a savings potential between 5 and 25% of the projects life cycle cost.

2.2.2.3.4 Scheduling

Analyzing a schedule with a 4D model is done by attaching 3D objects to construction activities. According to Songer et al. (2001b), "the quality of a schedule is dramatically improved when the scheduler has access to a 3-D design representation." Several specific benefits are presented below.

For schedule development, Songer et al. (2001b) had participants create simple schedules from either 2-D, 3-D or 3-D walk-thru representations of a simple section of a pipe rack, and then analyze the schedules to see if there were any out of sequence or missed activities. The results showed that 3-D walk thru had the least amount of errors. The improvement over 2-D is because “as the scheduler’s spatial comprehension of the design is improved, the scheduler can devote more resources to creating a quality schedule”. This was particularly true for complex configurations. Also with 3-D CAD and walk-thru, the experience of the scheduler becomes less important due to “simplifying the comprehension of the design with 3-D and walk-thru.”

For reviewing schedules Koo and Fischer (2000) found that while putting together the 4D model for their case study there was not enough detail for the exterior elements to “show a clear view of how these elements were actually [supposed to be] built”. For example all of the structural steel (columns, beams, trusses) for both floors were a single, 15 day activity. This problem was discovered when linking the 3D objects to schedule activities. Koo and Fischer (2000) also found that after linking all the objects with the schedule activities, there were activities that did not have a link, which means the original scheduler missed the installation of those items. Songer et al. (2001a) also tested if 4D models could improve the schedule review process. They had participants evaluate a schedule given to them and see if they could find errors. First they used a 2-D drawing to find errors, corrected those errors, and then created a 4D animation with the corrections. They then analyzed the 4D model to see if there were any more errors detected. The results showed that more errors and safety issues with regard to overcrowding were discovered with the 4-D animation.

2.2.2.3.5 Time-Space Conflicts

Three dimensional models are able to check if the design has space conflicts such as MEP conflicts, but they cannot analyze if there will be conflicts while construction is happening. According to Koo and Fischer (2000), 4D models are able to show “spatial constraints on the site and in the building which allows users to verify whether a component can be physically placed or where a crew can work in a certain location.”

Koo and Fisher's (2000) case study had three activities (electrical rough in, overhead HVAC rough in, and plumbing rough) executed at the same time on the master schedule. With only the master schedule, the project team was unable to determine if that sequence would create congestion problem. After creating the 4D model, it showed that the three different crews would have to be working in a limited space which could cause potential conflicts. Koo and Fischer, 2000 also found 4D CAD could be used to "detect potential site logistical challenges and accessibility problems." Specifically, one set of stairs on the project was scheduled to be installed early to allow access to the 2nd floor; however, when access was needed to the stairs other work was going on that limited access. The second set of stairs was not scheduled to be complete until after the work blocking the first set of stairs was clear. This meant there was a possible delay to work on the 2nd floor because there was not access. The second set of stairs should have been re-sequenced to an earlier start date to provide access to the 2nd floor. Another example is that the overhead HVAC system for the 2nd floor was scheduled before the 2nd floor slab and truss were completed, thus not giving the workers a platform to work on. Also, the roof was not completed either so there would have been no support for the HVAC to hang from.

2.2.3 3D and 4D for Transportation Projects

Three dimensional and 4D visualization research for transportation has lagged behind the amount of research complete on buildings. According to Kim et al. 2011 "it is clear that there is a lack of 4D CAD application in the area of civil engineering." This is because most of the research for 3D and 4D modeling has "targeted architectural constructions" (Kim et al., 2011). Kim et al. (2011) proposes three strongly tied reasons of why "there is a lack of 4D applications in civil infrastructure construction." First, "civil engineering facilities are more heavily influenced by harsh conditions than architectural facilities". Second, "construction activities are not well-organized in simple patterns, as not many activities are repeated in a civil engineering project." In building construction floor plans usually are repetitive, thus making it easy to create a 4D model for a building (Kim et al., 2011). Third, "civil infrastructure, in general, spans over a larger geographical area than do architectural facilities...which is the cause of their close interaction with the natural environment."

The issues mentioned above certainly present some challenges for implementing 3D and 4D visualizations on transportation projects, but those projects that are challenging could benefit the most from implementing this technology. According to Easa et al. (2002) "increased demands for system wide capacity, efficiency, and safety have led to increasingly intricate [transportation] systems that require effective management". Even though transportation visualization has been slower to develop than buildings, the methods that have been extensively used in urban planning and building visualization are being adopted by transportation because the methods effectively communicate project information (Liapi, 2003). The same categories used for buildings above, which were developed by Koo and Fisher (2000), are used to categories transportation below.

2.2.3.1 Visualization Tool

As a visualization tool, 3D and 4D models provide the same synthesis of information in for transportation projects as it does to buildings. The applications are just not very different from each other and not as numerous.

2.2.3.1.1 Public Involvement

The most common use of visualization in transportation projects is for placing them within their existing or envisioned built or natural context by means of photorealistic representations (Liapi, 2003). This is because "the public expects relatively realistic views" (Landphair and Larsen, 1993). Specifically, Bailey et al. (2002) tested three types of photorealistic visualization on a highway improvement project in the Bluegrass Region of central Kentucky during several focus group meetings: 2D photos, 3D models, and virtual reality (4D driving perspective). Bailey et al. (2002) found that the 3-D visualizations were the most preferred due to their "significantly more realistic detailing and texturing." Also, that "virtually reality was not considered much of an advantage" as the 3D model allowed more freedom to navigate and had better rendering (Bailey et al., 2002). Liapi (2003) used photorealistic representations to communicate changing traffic control measures to the traveling public during the construction phase, rather than the planning phase. This was done by uploading 3D animations of the view along the driver's paths to the local DOT website as seen in Figure 2-3.

Figure 2-3 Snapshot of Liapi's (2003) 3D Animation of Driver's Perspective for Routing Traffic during Construction

2.2.3.2 Integration Tool

Similar to buildings, one of the most valuable benefits of 3D and 4D visualization is the ability to improve communication and integration. Liapi (2003) states "The effective communication of project planning and scheduling information for visual evaluation is the main advantage of 4D models." Also, according to Kim et al. (2011), 4D models are "quite helpful for the smooth execution of the project, especially in the area of communication management." Specifically, because with the use of the 4D model, "the engineers for the contractor could easily communicate with the engineers for the subcontractors" (Kim et al., 2011).

Liapi et al. (2003) had very productive meetings where several different schedule alternatives were actually created during the meetings and then displayed side by side for comparison. The contractors and engineers were able to agree on a most preferred schedule during those meetings. Gau (2009) found that the 3D and 4D CAD models of the Woodall Deck project were very useful to communicate the nature of the project and specific topics during meetings involving TxDOT project team members. One of the topics was beam placement options where while watching 4D animations, the project team was able to “avoid misunderstandings and thus save time” (Gau et al. 2009).

2.2.3.3 Analysis Tool

As compared to buildings, the types of analysis that are completed with the 3D and 4D models are very different.

2.2.3.3.1 Traffic Planning

A significant difference between construction scheduling for standard projects and highway interchange projects, is that the construction phasing of the latter is directly related to traffic planning (Liapi, 2003). Therefore it is of critical importance that the “animation of the construction process also displays traffic planning measures” (Liapi, 2003). Liapi (2003) accomplishes this in the visualization system by “making lane indications graphical objects that are represented with activities added to the schedule” (Liapi et al., 2003). That way the 4D model can be of value to traffic engineers and contractors (Liapi, 2003).

2.2.3.3.2 Time-Space Conflicts

According to Liapi et al. (2003) “3-D modeling, as a graphical representation methods, is closer to the representation of the physical reality of a structure than 2D plans, and can, in principal, provide a better understanding of the aspects of a project that depend on spatial constraints.” Liapi et al. (2003) realized this information while building a visualization system for construction scheduling and traffic planning. This system was tested on the first phase of the “Dallas High Five” project, more specifically the Coit Bridge, and provided “effective feedback in terms of alternative schedules and allowed TxDOT personnel to make better decisions” (Liapi et al., 2003). Specifically the early construction of an overpass was identified by TxDOT engineers as a potential problem in the proposed contractor’s schedule.

2.2.4 3D Simulation

3D simulation is reviewed in its own section because there is no real difference in application or benefits between buildings or transportation projects. It is a specific type of 4D model where a specific activity is analyzed. Simulation models can provide a significant amount of information about a single activity, similar to how a 4D model does for the entire project. However, due to the time consuming process of creating 3D simulations, they are mostly done for activities using expensive resources that are repetitive, such as the use of cranes (Manrique et al., 2007, Kim et al., 2011). For this review, Manrique et al. (2007) used 3D simulation to animate the tilt-up process for 108 panels, Kim et al. (2011) animated derrick crane operations on a cable stay bridge, Lu et al. (2009) animated the erection of columns, and Kamat and Martinez (2001) animated earth moving operations.

2.2.4.1 Benefits

According Kim et al., (2011) 3D simulation models "were proven to be good tools for planning, constructability analysis, and communication." Specifically, errors can be avoided by analyzing the installation sequence with the 3D animation (Manrique et al., 2007). Some examples are listed below.

For Manrique et al. (2007) tilt-up panel erection case study decisions were modeled in 3D before any operation at the construction site which "helped to understand the installation sequence and helped to modify it according to space constraints. Another benefit includes reducing uncertainty of construction operations (Manrique et al., 2007). Kim et al.'s (2011) case study, the Cheongpoong Grand cable-stayed bridge, construction engineers involved in the project had a concern when the edge girders were moved from the trailer to the installation site they would collide with the pylon. By viewing the continuous-event simulation they found that "the location of the derrick crane and the sequential order of the construction tasks had to be changed" or there would have been a collision.

2.3 Conclusions

Transportation projects are unique projects that have many issues such as ROW acquisition, traffic control, and utilities. Also, the issues that face all projects, such as reducing costs and schedule are compounded on transportation projects because of reduced funding and increased ridership on roadways. To help solve some of these issues projects should utilize constructability. The benefits have been proven over the past 25 years as a way to reduce schedule and costs with a cost to benefit ratio of 10:1. The issue with constructability is implementing it effectively. To realize the full benefits, constructability should be utilized from the very beginning of the project at the conceptual planning phase. One of the tools to support implementation is 3D and 4D visualization. Significant research has been conducted on the benefits of 3D and 4D visualization for building projects. The visualization tools can improve the understanding of projects, communication between project players, and complete several types of analysis such as schedule review and estimating. The benefits and applications of 3D and 4D for transportation project research is still lagging behind building projects. Some progress on transportation research has been made by learning from the research on from buildings, but there are still areas that are lacking. Kim et al. (2011) states that "more case studies are needed for a comprehensive assessment of 4D CAD applications for other types of civil engineering construction". One of the areas is applications in the early planning phases, which this thesis presents.

2.4 Summary Table

Table 2-1 below is a summary table of the benefits from previous research. The topics listed are the ones most applicable to the content of this thesis. The different pieces of literature are organized by the type of tool they are (as above in the text) as well as the benefit category.

Table 2-1 Summary of Literature

Type of Tool	Categories of 3D/4D Benefits	Literature
Visualization	3D Spatial Visualization	4D models are able to show "spatial constraints on the site and in the building which allows users to verify whether a component can be physically placed or where crew can work in a certain location" (Koo and Fisher, 2000).
		According to Liapi et al. (2003) "3-D modeling, as a graphical representation methods, is closer to the representation of the physical reality of a structure than 2D plans, and can, in principal, provide a better understanding of the aspects of a project that depend on spatial constraints
	Communication of Information	The 4D model the design team created as part of the bid package. This was done to visualize problematic design areas or construction sequences. That way, potential bidders were better to fully understand the design and construction work. This resulted in bids closer in proximity to each other with fewer contingencies. (Gao et al., 2005)
	Synthesis of Information	Koo and Fischer, (2000) found that as a visualization tool, 3D and 4D models "obviate the need to conceptualize the association between components and activities to comprehend the schedule…also [the models] show the spatial constraints between components, enabling users to detect space-related conflicts".
Integration	Increased Communication	For transportation construction, Kim et al. (2011) found 4D models were "quite helpful for the smooth execution for the project especially in the area of communication management".
	Coordination and Integration	With these 3D and 4D models "the project team could communicate product and process knowledge more efficiently" (Hartmann and Fischer, 2008)

Table 2 – 1, cont.

Analysis	Schedule Analysis	Koo and Fischer, (2000) found 4D CAD could be used to "detect potential site logistical challenges and accessibility problems". The 4D model they created help them identify a scheduling issue.
		Songer et al. (2001b) concluded that "the quality of a schedule, both in terms of correctness and goodness, is dramatically improved when the scheduler has access to a 3-D design representation".
	Construction Process Analysis	Kim et al. (2011) studied the Cheongpoong Grand cable-stayed bridge where construction engineers involved in the project had a concern when the edge girders were moved from the trailer to the installation site they would collide with the pylon. When viewing the continuous-event simulation they found that "the location of the derrick crane and the sequential order of the construction tasks had to be changed" or there would have been a collision.
	Design Alternative Checking	To integrate traffic planning into the construction sequencing model Liapi, (2003) made "lane indications graphical objects that are represented with activities added to the schedule" (Liapi et al., 2003). That way the "4D model can be of value to traffic engineers and contractor" (Liapi et al., 2003).
		Ganah, et al. (2005) found that "3-D modeling helps in identifying any missing information for building a particular component" and that "by modeling design details [in 3D], decisions can be made on the design and the results can be seen before the construction start".
Simulation	Reduced Uncertainty	Manrique et al., (2007) also mentions another benefit of 3D modeling is reducing uncertainty of construction operations.
	Simulation of Construction	Monique et al., (2007) discovered one of the biggest benefits of 3D and 4D modeling is simulating projects in advance. Manrique et al., (2007) also mentions another benefit of 3D modeling is reducing uncertainty of construction operations.
		For a project with complex tilt wall construction Manrique et al. (2007) modeled decisions in 3D before any operation at the construction site, which "helped to understand the installation sequence and helped to modify it according to space constraints.

2.5 Research Questions

This thesis aims to develop some ideas about how 3D and 4D modeling technology can be utilized in early project phases to support constructability. In order to best accomplish this several questions should be answered.

What research has already been done in this area of work?

Previous research will provide both a framework for this new research as well as possible benefits that can be applied for this research.

What types of issues happen in construction that are caused by the design?

In order to determine the best way for 3D/4D to support constructability, the issues need to be well known.

What are the impacts those issues have on construction?

In order to determine if utilizing 3D/4D early in the project phase is worth the investment, the impact the issues cause on the project should be known. An issue that does not have a large impact on construction might not be worth the time and money to use 3D/4D.

What benefits from previous 3D/4D models can be utilized for early implementation.

Proven benefits from other research should be the first utilized and tested to see if they are applicable for early 3D/4D modeling.

What type of potential impact can early 3D/4D models have on those issues?

The impact of the 3D/4D technology should be documented. Both the type of impact as well as an quantitative impacts.

What level of detail in the models is needed for early implementation?

The level of detail in a model is one of the biggest factors in the cost and time of implementing it. Also, a certain amount of information needs to be available based on the type of issue being analyzed.

For this thesis, all of this work is accomplished by working on actual project case studies. The issues are drawn from previous knowledge of the projects as well as interviews with the project managers (PM). For those specific issues a potential frame work is presented on how 3D and 4D modeling in the early planning and design phases is discusses. The potential impact 3D/4D could have on the project is also included as well as details about what level of detail in the models is needed to create that impact.

Chapter 3: Case Studies

3.1 President George Bush Turnpike

3.1.1 Introduction

President George Bush Turnpike (PGBT) is a "30.5-mile, six-lane, significant east-west, limited access expressway within a major developing economic area in the northern half of the Dallas Metroplex" (NTTA, 2011). It passes through or along the cities of Garland, Richardson, Plano, Dallas, Carrollton, Farmers Branch and Irving as seen in Figure 3-1. PGBT is currently going through a 9.9-mile eastern extension from State Highway (SH)-78 in Garland, east to Interstate Highway (IH)-30. The addition is a six-lane toll road that will pass through Garland, Sachse, Rowlett, and will include a one-mile bridge over Dallas' Lake Ray Hubbard with a major interchange at IH 30, as seen in Figure 3-2. The North Texas Tollway Authority (NTTA) is the owner and operator of PGBT. More specifically the NTTA is "a political subdivision of the State of Texas under Chapter 366 of the Transportation Code, is empowered to acquire, construct, maintain, repair and operate turnpike projects; to raise capital for construction projects through the issuance of Turnpike Revenue Bonds; and to collect tolls to operate, maintain and pay debt service on those projects" (NTTA, 2011). NTTA has acquired the entire ROW for the eastern extension and is building all of the sections of the eastern extension but the final section (section 32). TxDOT is building section 32 which includes the bridge over Lake Ray Hubbard and the major interchange with I-30. The total cost for the eastern extension is $958 MN. The TxDOT portion of the project is $180 MN. Construction on the TxDOT portion started December 2008 with an estimated total completion of June 2012 and bridge and ramps openings of December 2011. The TxDOT portion of the eastern extension is the focus of this case study.

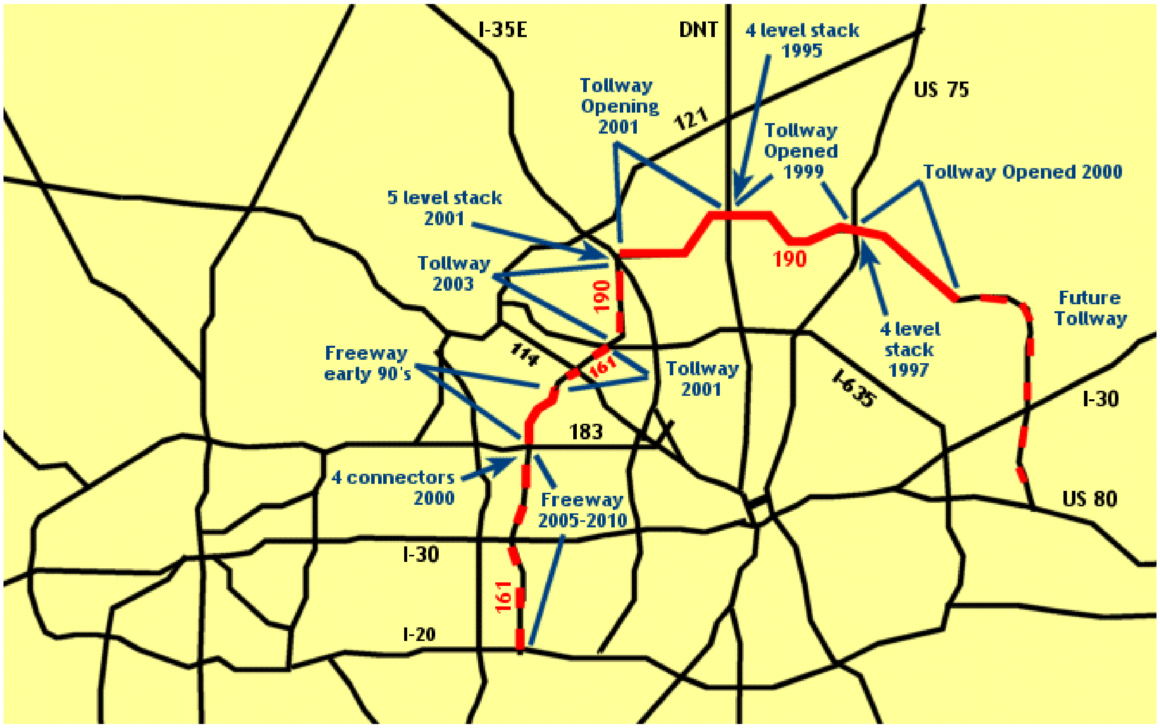

Figure 3-1 Overview of PGBT route in Dallas – red (Texas Freeways, 2000)

All sections are complete except for the eastern extension near 1-30 and US 80. PGBT is technically 190, but 161 connects directly to 190.

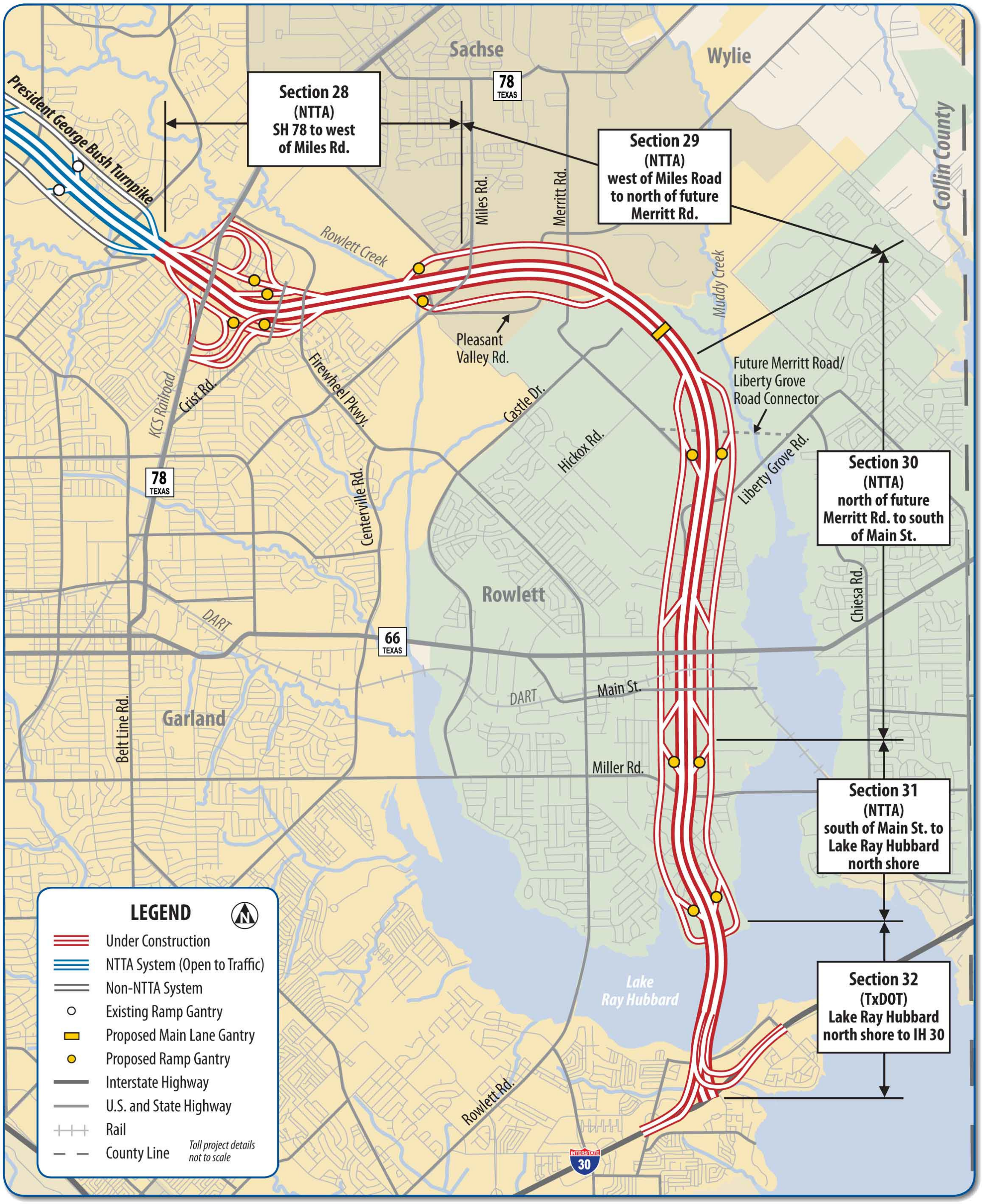

Figure 3-2 Map of PGBT Eastern Extension (NTTA, 2011)

TxDOT's scope of the eastern extension is section 32 including the bridge over Lake Ray Hubbard and the major interchange with I-30

3.1.2 Project Orientation

The 1.0 mile bridge across the lake is a green field project with nothing previously existing. However, I-30 and the PGBT/I-30 intersection have existing construction that must be demolished.

3.1.2.1 Existing Conditions

The area where PGBT and I-30 will connect has two existing roads, several homes, and an apartment complex that will be demolished. A satellite image of the area for reference is seen in Figure 3-3. The 3D model of the area is seen in Figure 3-4. At the location where PGBT will intersect with I-30, I-30 is a 3 lane highway in each direction with 3 lane frontage roads on each side (west bound and east bound). There are also several side roads that will be affected off the east bound frontage road (EBFR) while I-30 is being reconstructed. The side roads are Seaport Drive, Lake Ray Hubbard Parkway, Marina Drive, and Peninsula Way.

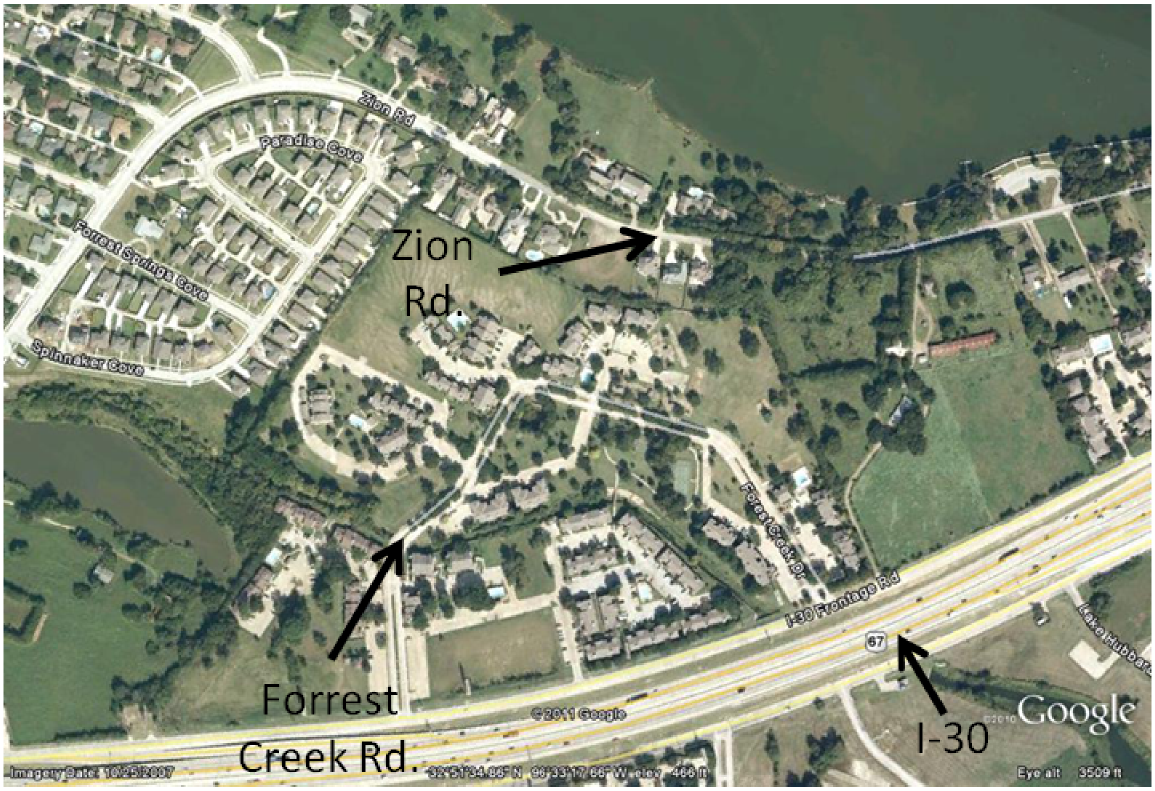

Figure 3-3 Satellite Image of Existing Conditions Where PGBT Will Intersect I-30. (Google Earth, 2011)

I-30 runs east and west. Zion Road runs along the lake with several homes and Forest Creek Drive makes a half loop for access to an apartment complex off I-30 west bound frontage road. All will be demolished for the new intersection of PGBT and I-30. (North towards the top of the picture)

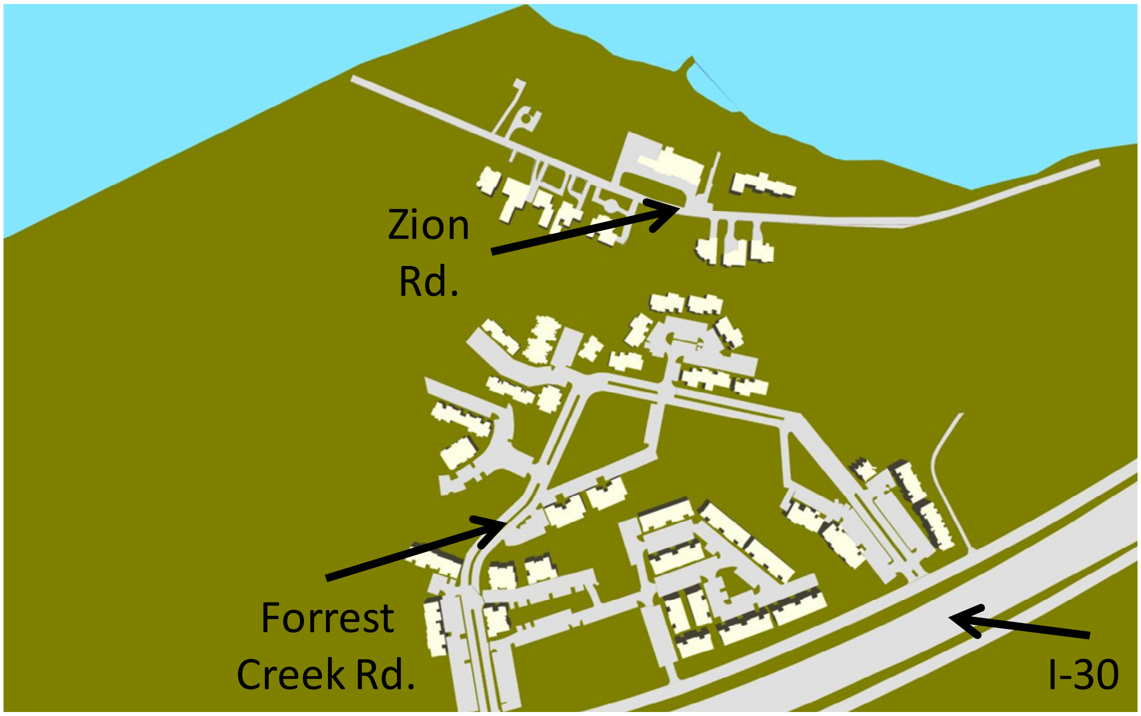

Figure 3-4 3D Model of Existing Conditions (plan view)

Roads modeled are I-30, Zion Road, Forest Creek Drive, homes and apartment complex. The lake is blue and solid earth is brown. All will be demolished for the new intersection of PGBT and I-30. (North is towards top of picture)

3.1.2.2 New Construction

For comparison of existing conditions to completed construction Figure 3-5 and Figure 3-6 are updated views of Figure 3-3 and Figure 3-4. The PGBT bridge that crosses Lake Ray Hubbard is a three lane highway in each direction (north and south) as seen in Figure 3-7. There are four direct connectors that connect PGBT and I-30. Each PGBT direction (north and south) has a direct connector for the east bound (EB) and west bound (WB) directions of I-30 as seen in Figure 3-8. There are also two connector roads from PGBT that dead end into the I-30 WB frontage road (WBFR), creating an intersection that did not existing prior to construction as seen in Figure 3-9. The other major road to be constructed is an extension of Zion road which currently runs along the lake's edge. Zion road will intersect the WBFR where Forest Creek drive was, before it was demolished.

Figure 3-5 Satellite image of current construction (3/31/2011) for comparison with Figure 3-3

Most all of the direct connectors are complete. WBFR and WBML are complete. Zion Road extension and connector roads are still under construction. PGBT bridge is mostly complete.

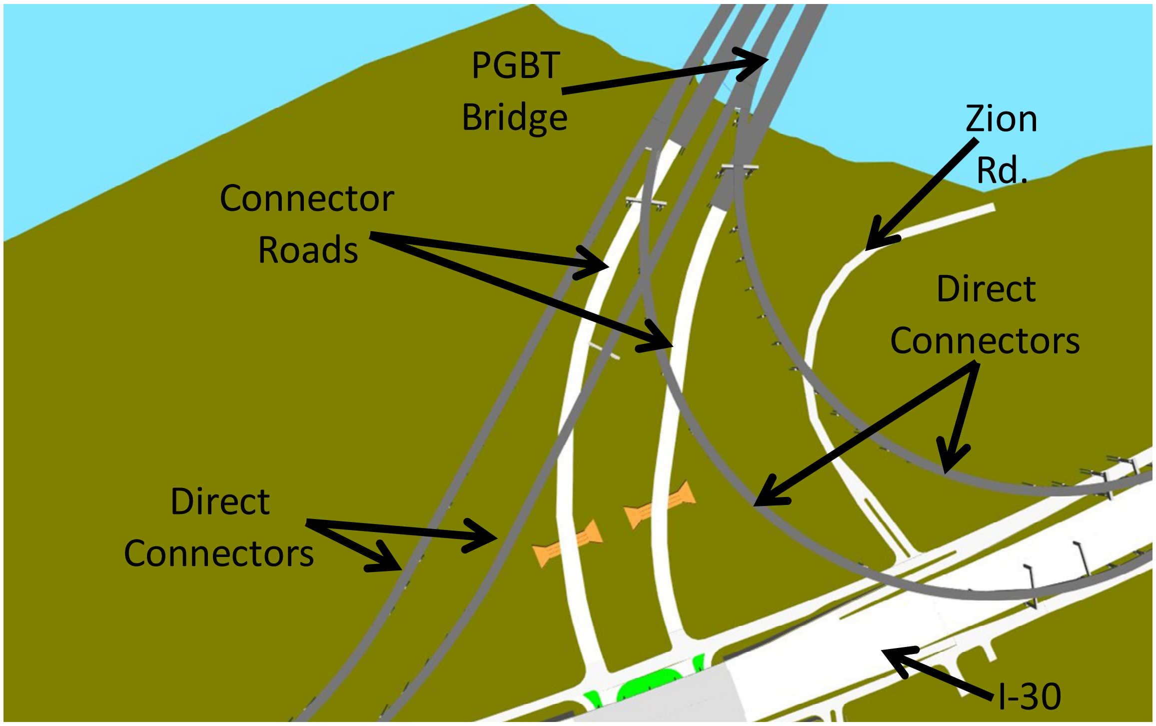

Figure 3-6 3D model of completed project with same view as Figure 3-4 for comparison. (plan view)

Direct connectors are shown in gray. Roads from PGBT connect to I-30 WBFR for new intersection are shown in white. Zion road extension is curved road from WBFR that will connect to existing Zion road along lake's edge. North is towards the top of the picture.

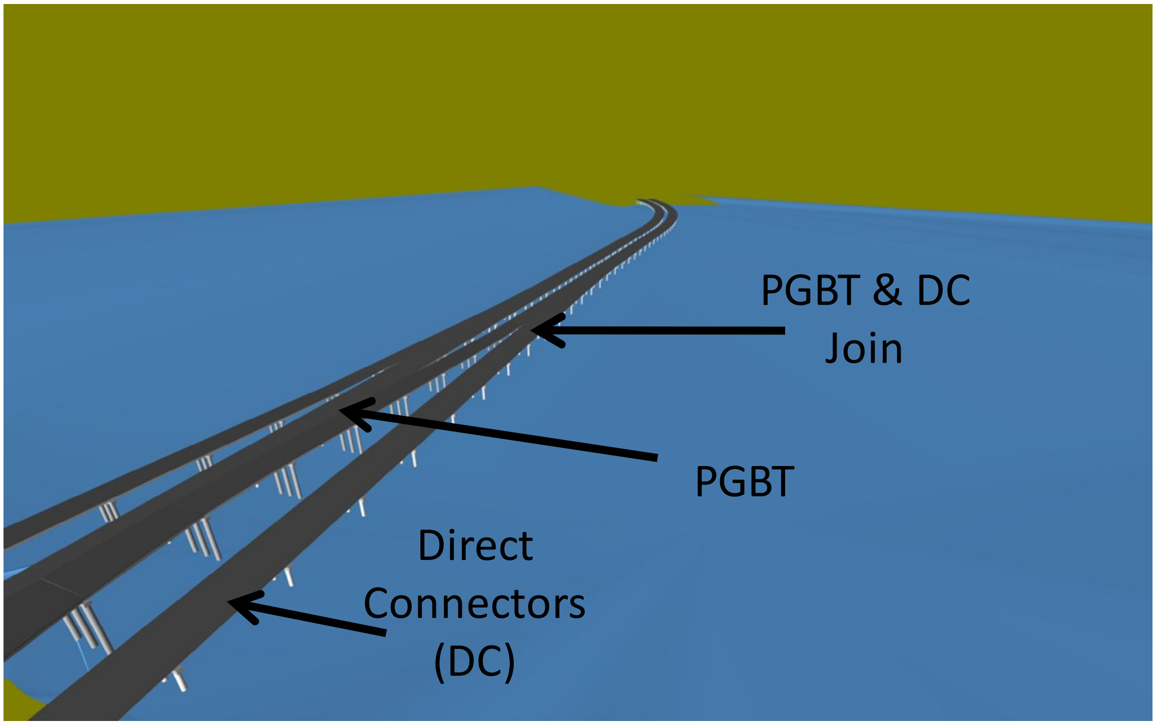

Figure 3-7 PGBT 1.0 mile long bridge crosses Lake Ray Hubbard. (looking north)

The bridge is 3 lanes in each direction (north and south). The direct connectors split off while still over water to connect to I-30.

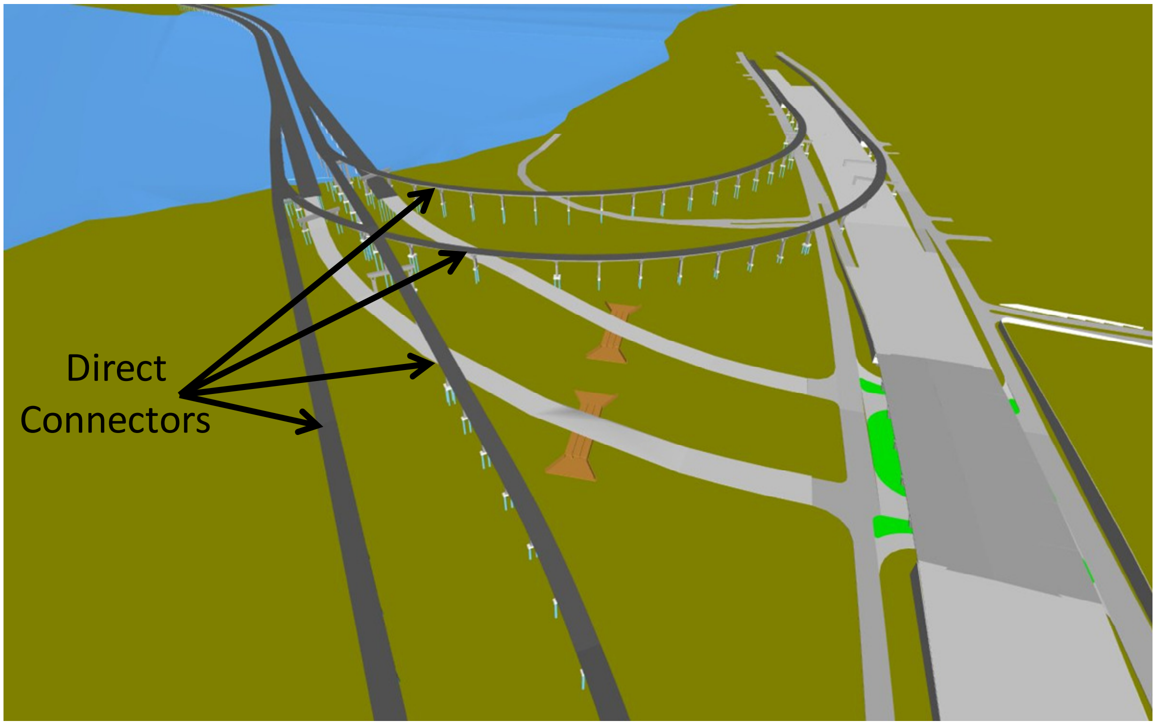

Figure 3-8 Direct Connectors

Direct connectors (4) connect both directions of PGBT to both directions of I-30.

3.1.3 Scope

A large scale overview of the project is presented here with a detailed list following as well as a photo sequence of the construction. The TxDOT contractor is responsible for the demolition of the apartment complex, Forest Creek Drive, part of Zion Road, and several houses on Zion road. Construction includes the bridge over Lake Ray Hubbard, the 4 direct connectors, connection of Zion road to WBFR, PGBT connection roads. Also included is demolition and reconstruction of I-30 with a new bridge to pass over the new intersection of PGBT and I-30 as seen in Figure 3-9. Retaining walls, culverts, drainage, electrical and landscaping are included as needed for the new roads. Utility relocation is required for the new construction, but not a part of the contractor's scope.

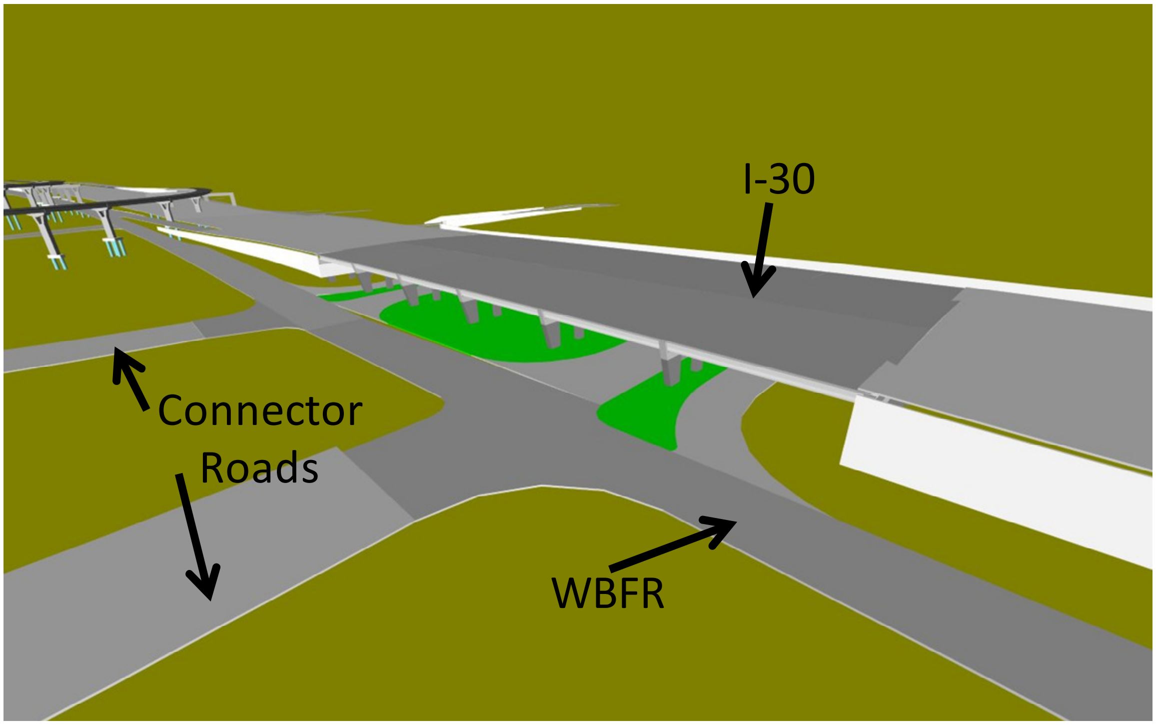

Figure 3-9 The Intersection of PGBT and I-30 Frontage Roads. (looking SE)

This intersection allows drivers who cannot access the roads via direct connectors. It also requires a bridge for the I-30 main lanes to pass over.

Demolition

- I-30 main lanes and frontage road – reconfigured and reconstructed
- Forest Creek Road
- Zion Road
- Houses ~ 7
- Apartment buildings ~ 35
- Side road stub outs
  - Seaport Drive
  - Lake Ray Hubbard Parkway
  - Marina Drive
  - Peninsula Way

Construction

- PGBT Bridge - 1.0 mile (3 lane each direction)
    - 52 bents
- Zion Road - 1400 LF (1 lane)
- DC01 – 32 bents (1 lane)
- DC02 – 25 bents (1 lane)
- DC03 – 20 bents (1 lane)
- DC04 – 29 bents (1 lane)
- Drainage Culverts - 5
- Storm Sewer Lines – 16
- Inlets - 49
- Retaining Walls – 17
- I-30 Bridge
    - 7 bents/abutments
- I-30 – 7000 LF
    - WBFR – 3 lanes
    - WBML – 3 lanes
    - EBFR – 3 lanes
    - EBML – 3 lanes

Begin Photo Sequence of Work

(all photo have same viewpoint - plan view, north toward top of picture)

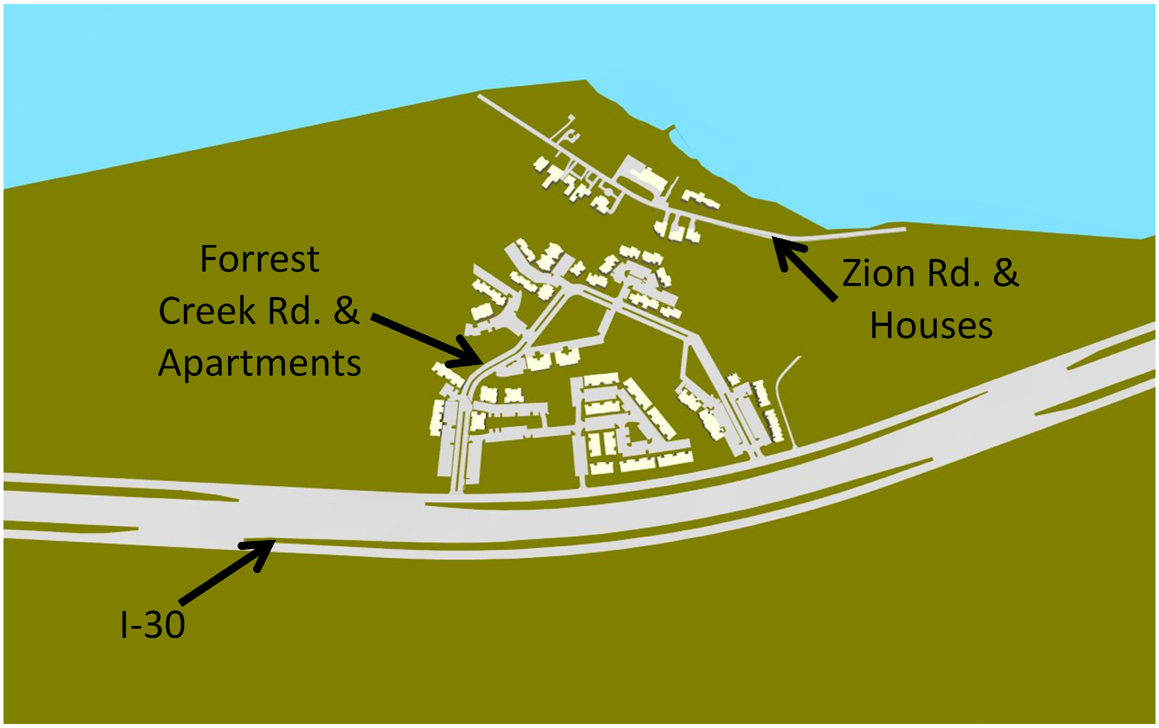

Figure 3-10 Existing Conditions of Project before Construction

Apartment complex located off I-30 and a road with homes near the lake. All will be demolished with I-30 being reconstructed with a slight alignment change.

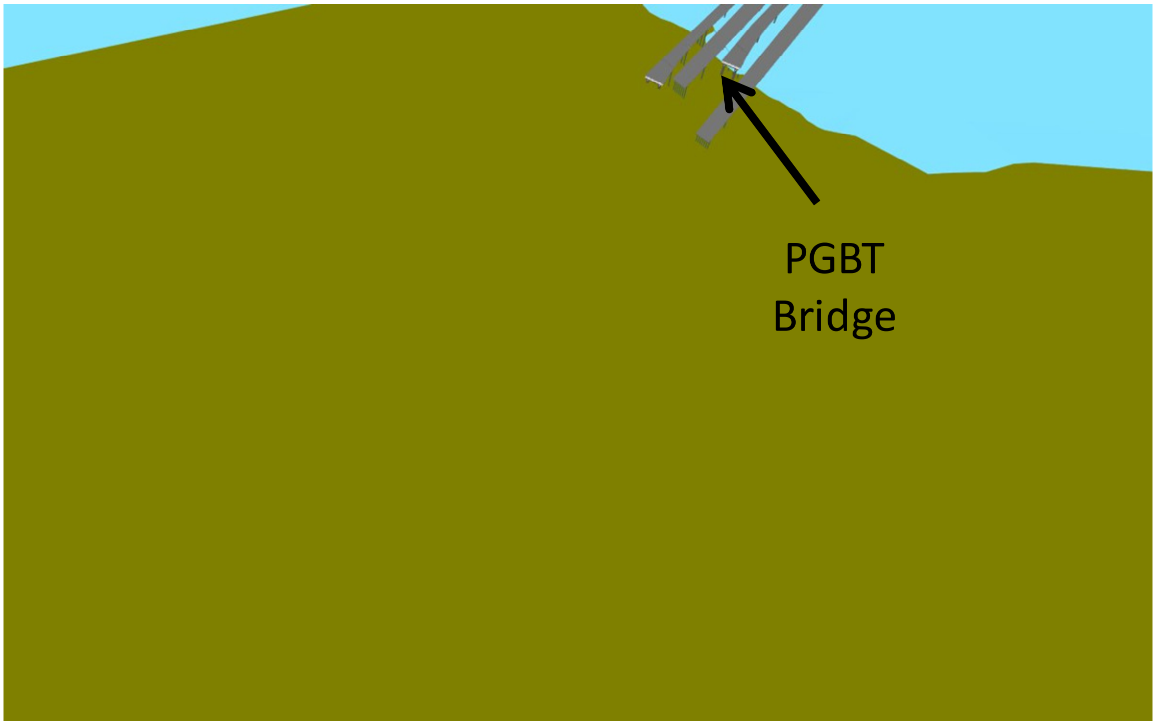

Figure 3-11 Construction of the PGBT Bridge NB and SB

The PGBT bridge is built almost as a separate project as it is built on a green field site. The TCP has the whole bridge in Phase 1. The north bound portion is constructed, followed by the south bound portion. Each portion starts at the south end and works towards the north.

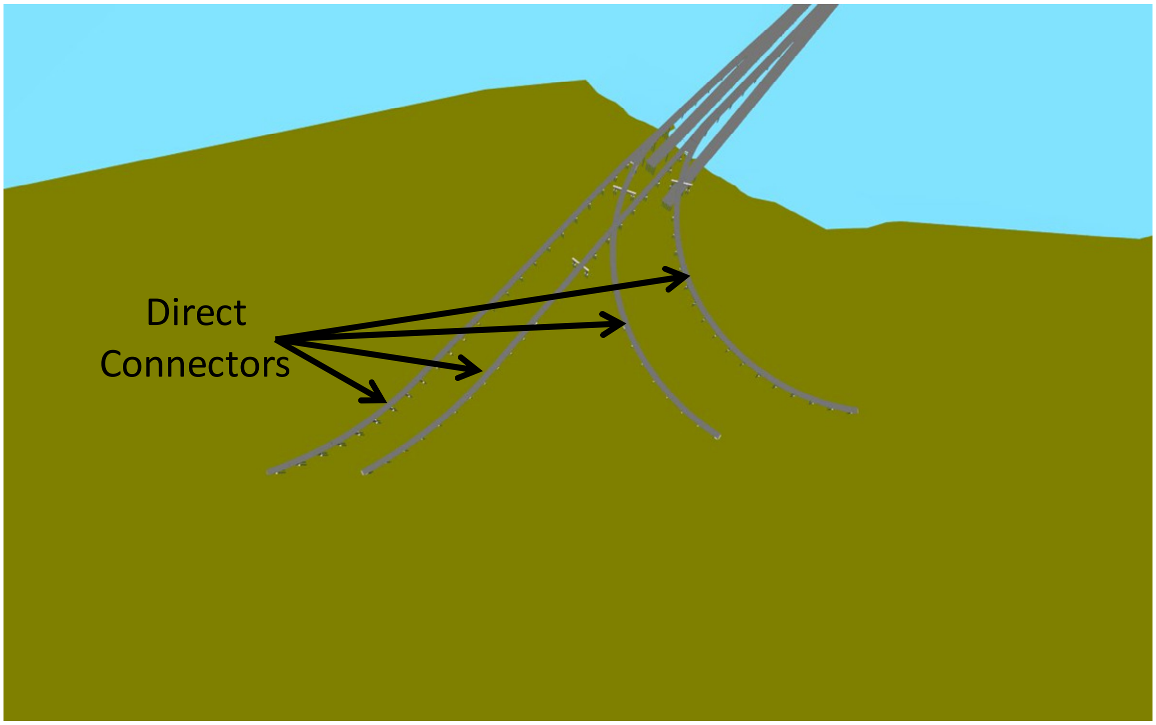

Figure 3-12 Construction of Partial Direct Connectors

After demolition of the apartment complex and roads, most of the direct connector area is a green field project. All four of the direct connectors are built almost as a separate project much like the PGBT bridge up until they start crossing over I-30.

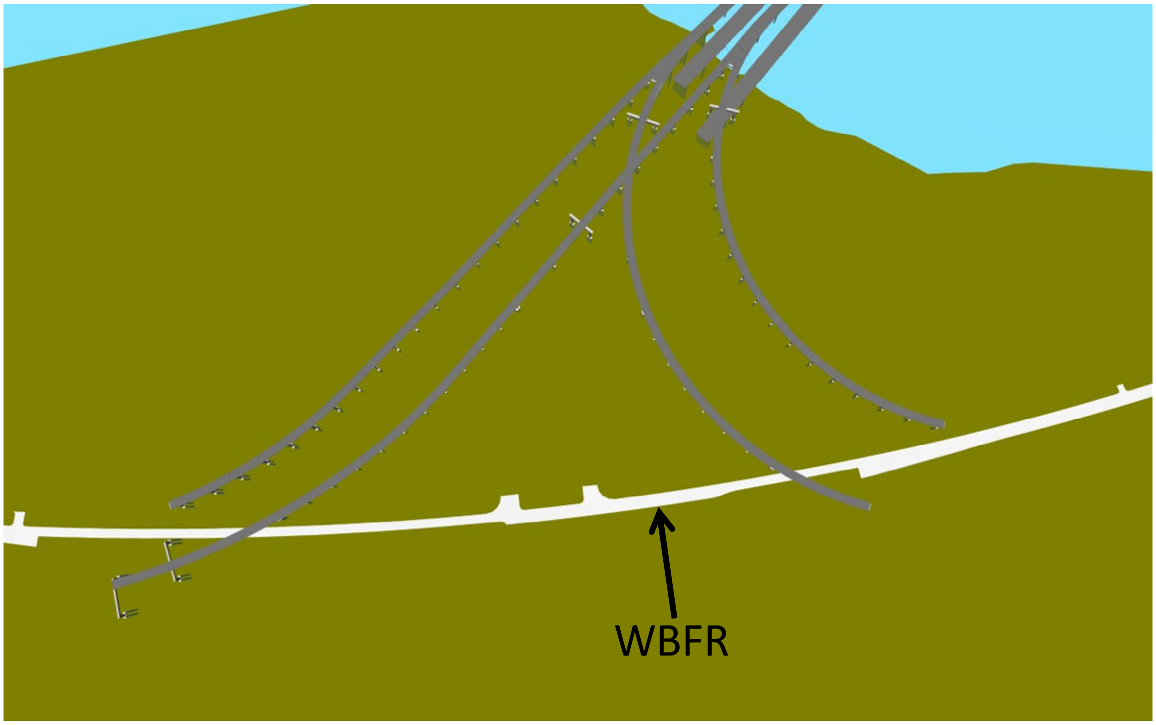

Figure 3-13 Construction of I-30 WBFR

The new WBFR is built slightly north of the existing one. The existing WBFR is reduced to 1 lane for work clearance and safety.

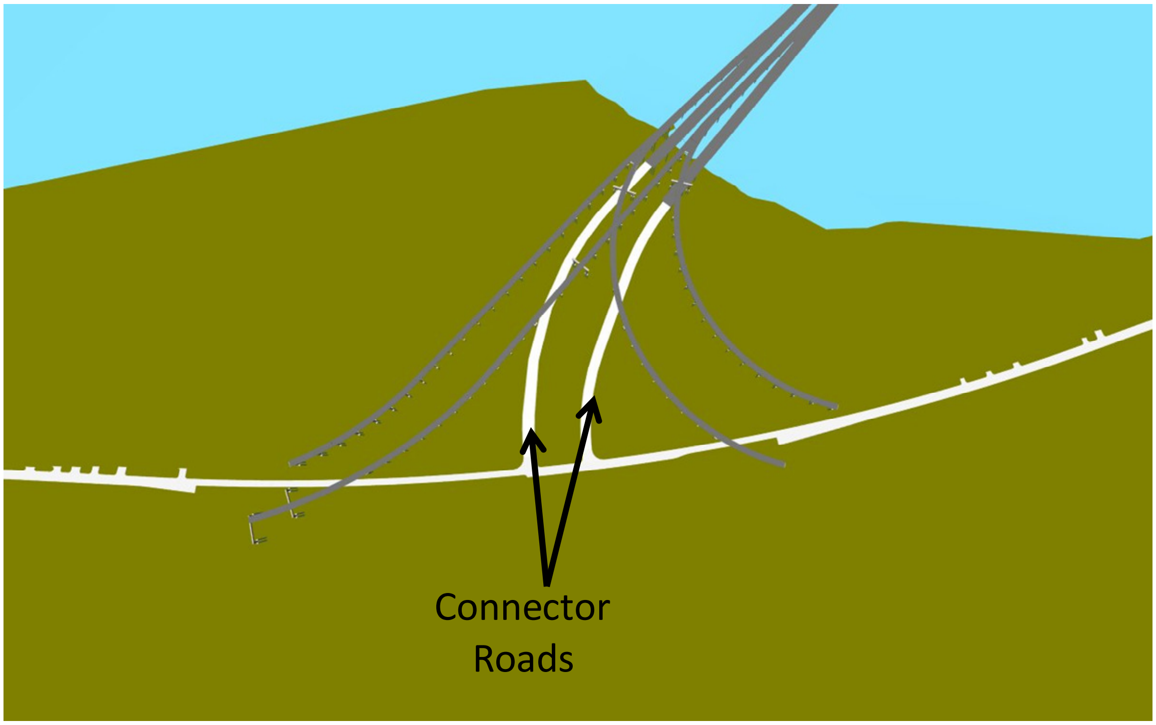

Figure 3-14 Construction of the Connector Roads

Once the new WBFR is constructed the connector roads to PGBT can be built because there is now space available.

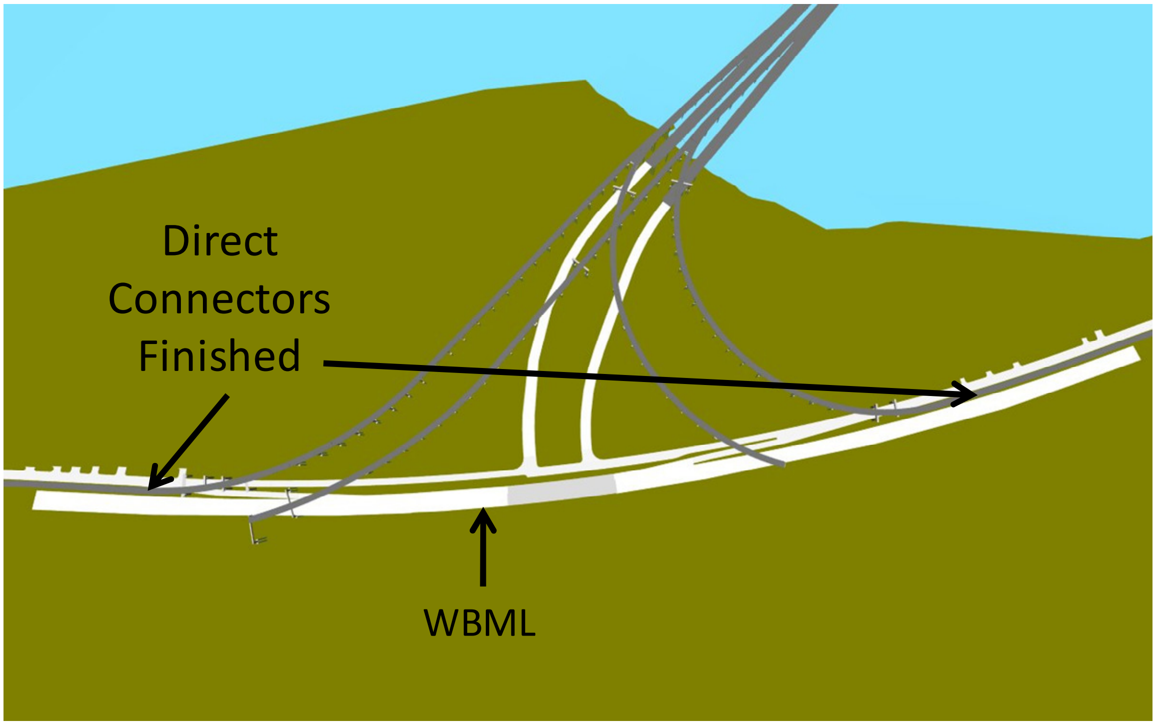

Figure 3-15 Construction of the WBML

Temporary pavement is added to the EBML on the south side so all traffic can be shifted to the EBML. This allows for the WBML to be reconstructed. Also since there is room, two of the direct connectors are completed to where they intersect with I-30.

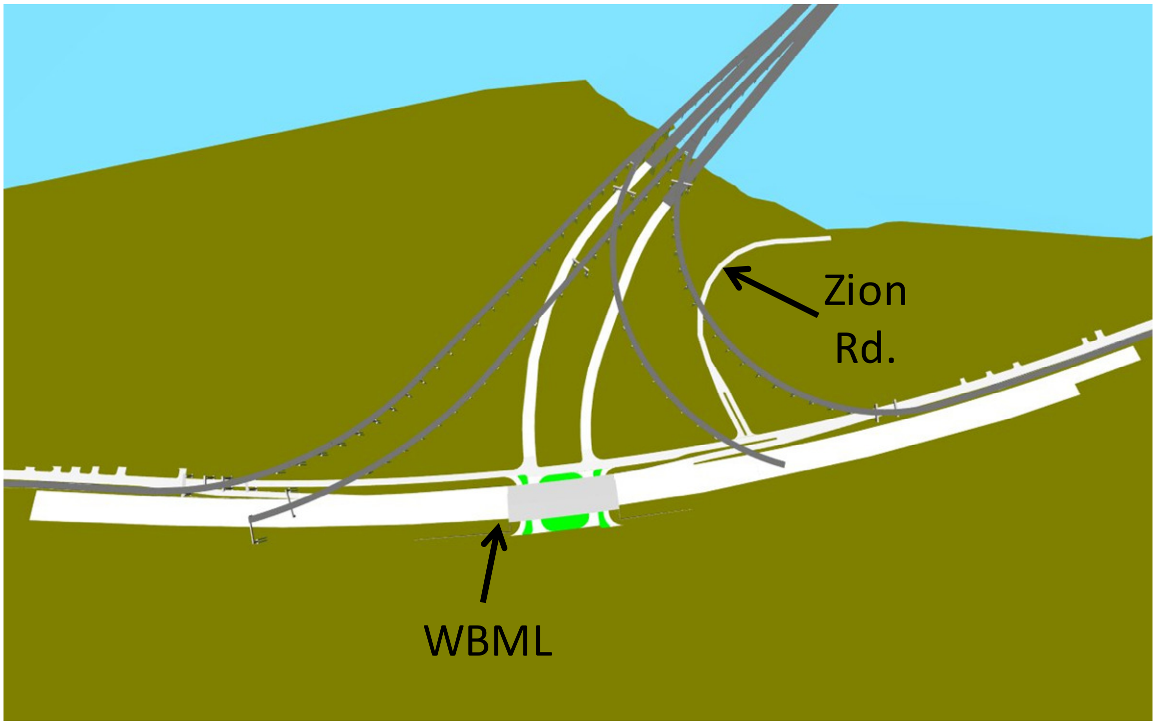

Figure 3-16 Construction of Zion Road

Once the work around the direct connectors and PGBT bridge are complete the Zion Road extension can be constructed. Also a little bit more width is added to the WBML while traffic remains on the temporarily expanded EBML. This added width to the WBML is wide enough to accommodate both EB and WB traffic for the next phase of construction.

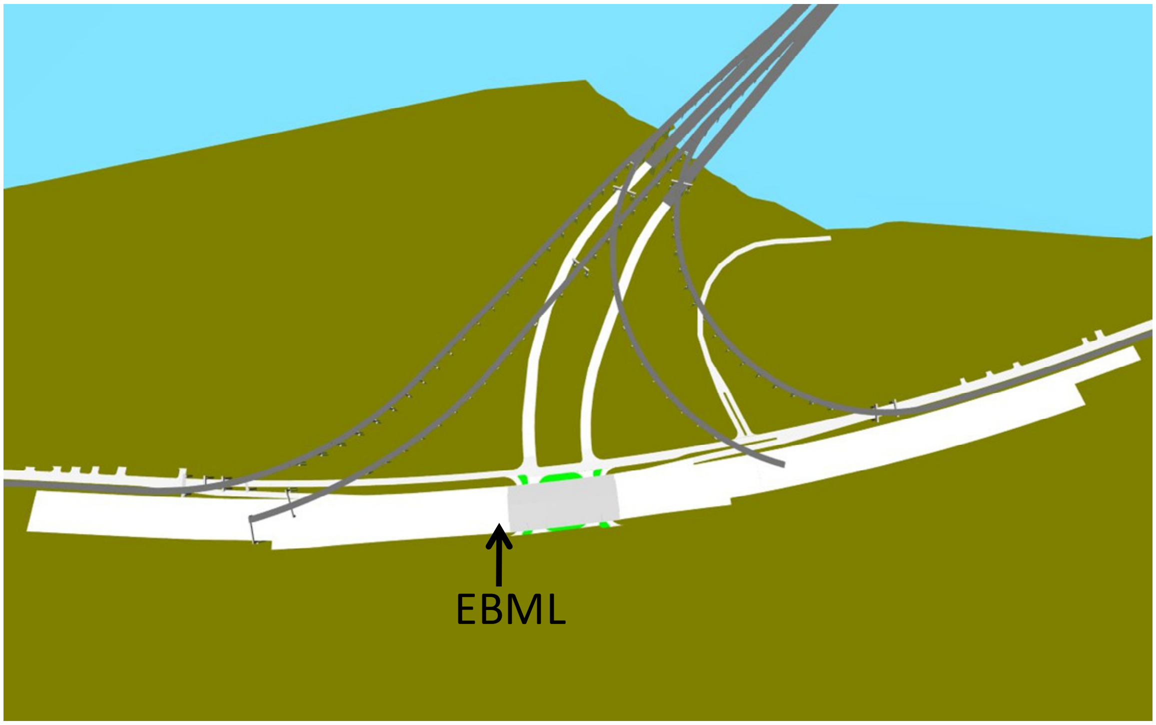

Figure 3-17 Construction of the EBML

The EBML are constructed as the permanent WBML are wide enough to shift both the WB and EB traffic to the permanent WBML.

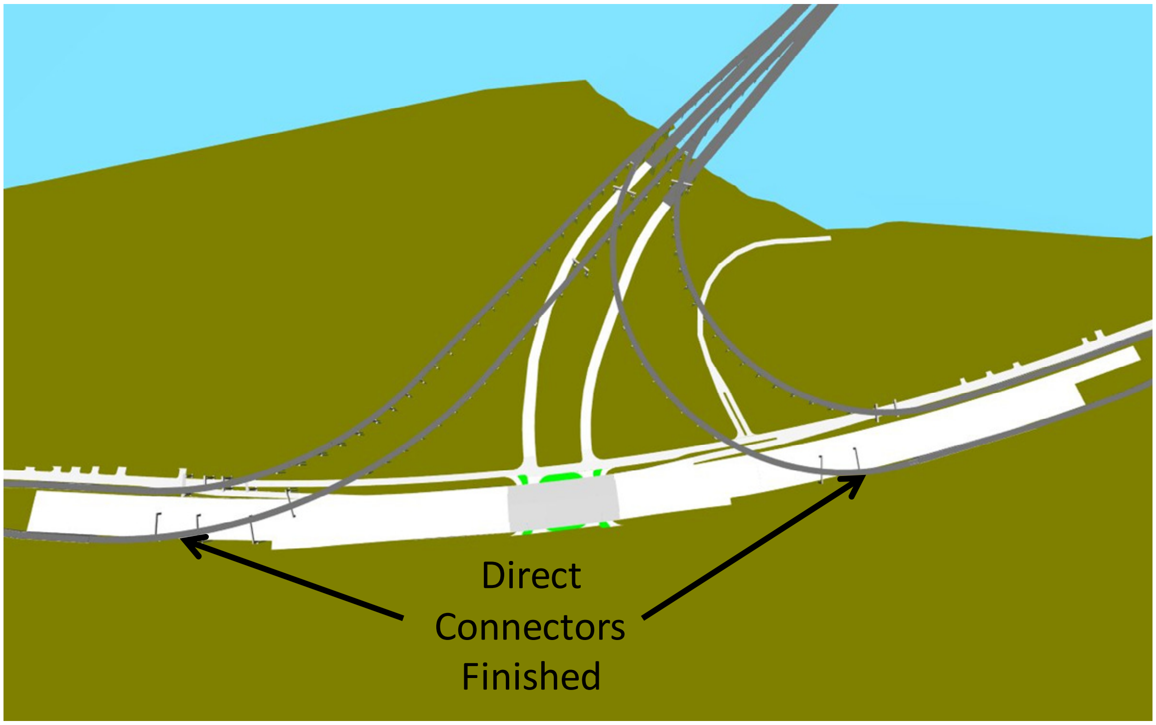

Figure 3-18 Construction of the Final Two Direct Connectors

The last two direct connectors can be completed because there is now room to work on them since the EBML is complete.

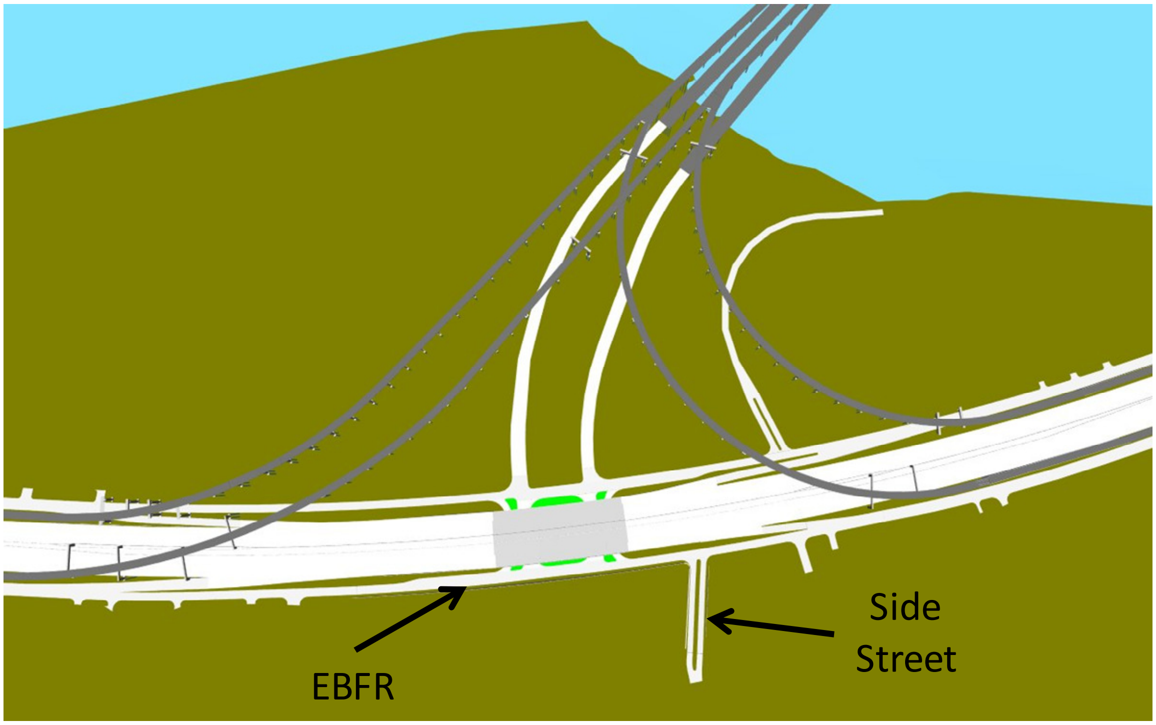

Figure 3-19 Construction of the EBFR and Side Roads

The EBFR is that last portion to be completed, along with the side road connections. The side roads were extended a small amount north due to the EBFR being moved north a small amount.

3.1.4 Challenges

3.1.4.1 Right-of-Way Acquisition

This project has several aspects that make it challenging. One of the biggest is the acquisition of ROW. This project has 38 different parcels to acquire including family homes as well as businesses. Several of the parcels had to be acquired through eminent domain which takes longer and is more work. This challenge is compounded because the acquisition is being done by NTTA while construction is being done by TxDOT. In order to complete the project on schedule, construction is starting very close to acquisition as seen in Figure 3-20. Two different entities working close together makes communication more difficult and therefore issues more likely.

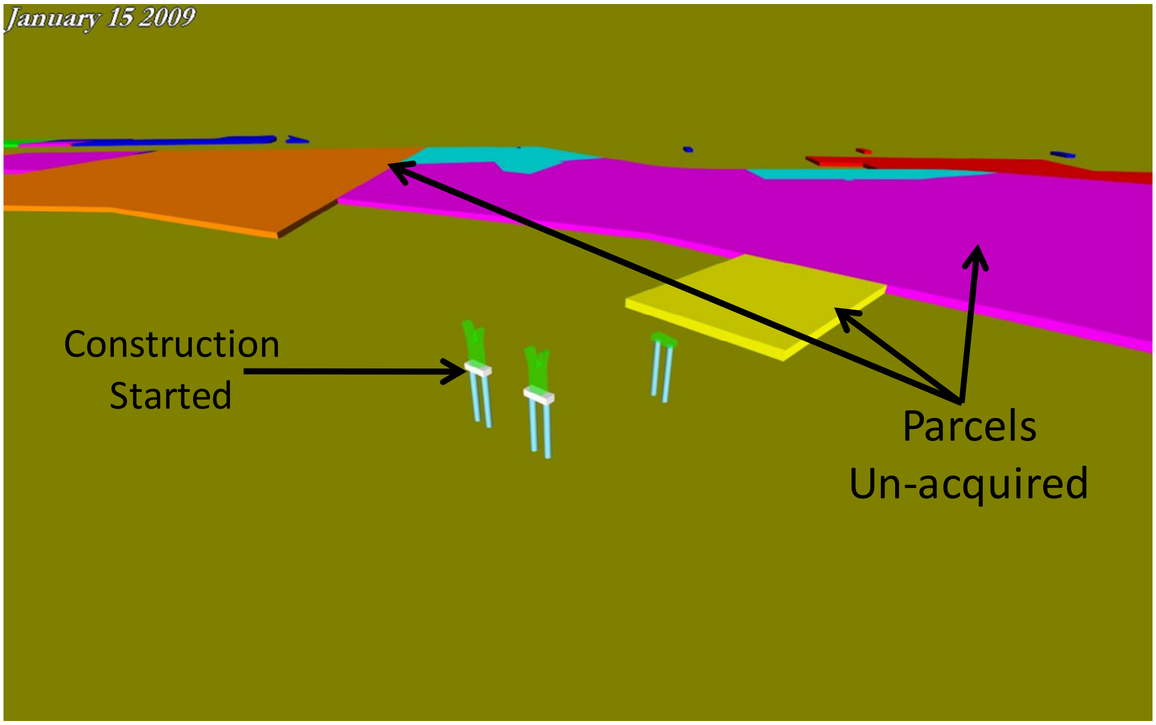

Figure 3-20 Construction Started Very Close to ROW Acquisition

The construction schedule is very close to the ROW acquisition schedule which means there is not much room for error or delays for acquisition, or construction will be delayed

3.1.4.2 Utility Relocation

This project has a large amount of utilities that require relocation. There are six total utility owners that have to relocate their lines; 3 power and 3 communications. Having so many utilities to relocate requires a great deal of coordination work. The lines run along I-30 and often cross under the side roads. Zion road also has utilities that cross under it. To further complicate things, the existing utilities have both aerial and under grounds lines which will all become buried lines. Burying the utilities is more work for the utility contractors and means more chances for incidents due to the underground work. Also, all of the utilities are very close to each other so having a large number of lines can create issues; such as having too many workers and/or equipment in one area, or one utility hitting another's line.

3.1.4.3 Existing Traffic

I-30 is a large and busy 6 total lane highway that must stay open to traffic as it is a part of the interstate system and links major cities. TxDOT is used to working with existing traffic so this is not a major issue, but it does create some complications. Existing traffic is a safety hazard for workers so it is very important to keep them safe while they are working so close to speeding cars and trucks. Existing traffic on I-30 also affects the construction of the direct connectors. For safety reasons construction cannot take place over open lanes of traffic, so coordinating beam placement and lane closures requires additional planning. All of this has been done before on other projects, but the existing traffic does add challenges that would not be there for a green field project.

3.1.4.4 Crossing Direct Connectors

In order to provide drivers with an easy connection between the two major highways, four direct connectors are needed. The direct connectors will connect southbound PGBT to both east and west bound I-30, and both east and west bound I-30 will be connected to north bound PGBT. In order to accomplish this there is a great deal of cross over work that happens, as seen in Figure 3-21. This cross over work that happens requires more thought and planning due to the 3D aspect of having roads cross over one another. Construction planners must make sure to sequence construction of the different roads so that there is adequate access to build the direct connectors. The crossing of direct connectors and roads is compounded because some of the direct connectors cross over I-30 which has traffic on it and is under construction. A significant amount of planning and coordination must happen to ensure the impact to traffic is as small as possible, construction of I-30 and the new bridge is completed, and the new direct connectors can be completed on time. Also, where all the connectors come together at the PGBT bridge there is only a small area to complete all of the different elements of the direct connectors. Such as pouring concrete, placing beams with a crane, etc.

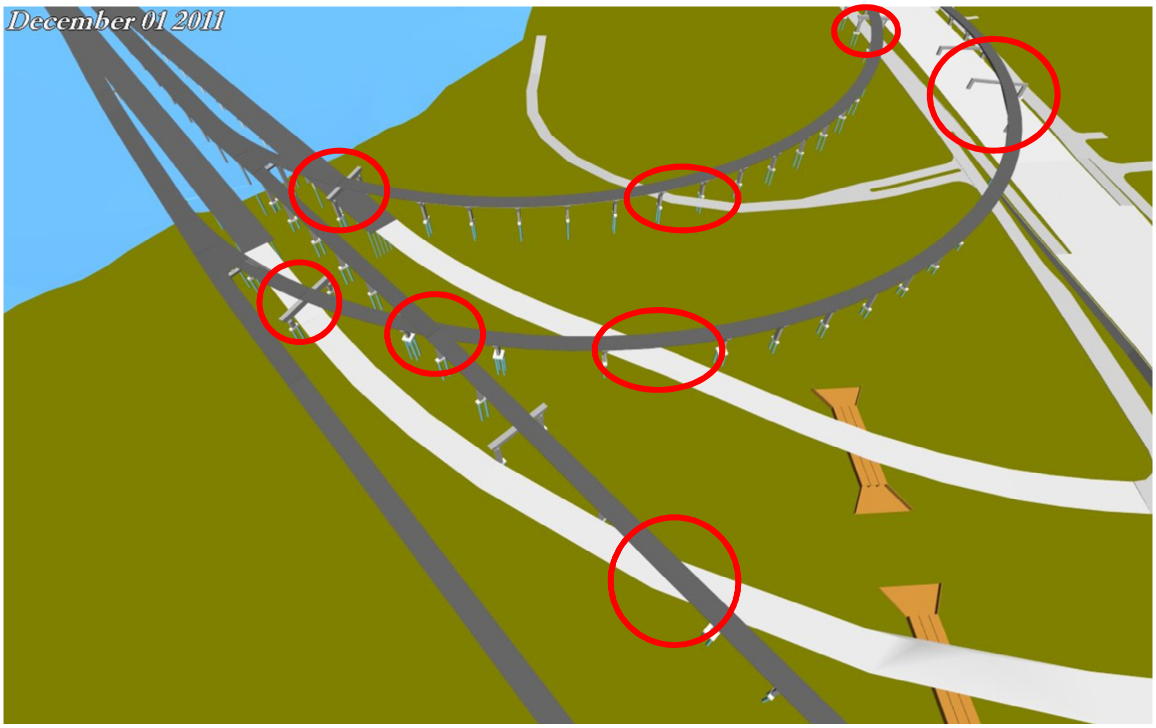

Figure 3-21 Direct Connectors Crossing Over Several Roads and Each Other (circled in red)

The direct connectors improve the flow of traffic for drivers once the project is completed. However, having direct connectors for all four connections requires the direct connectors to cross over other roads and each other. This adds complexity to construction planning because things are happening dynamically in all three of the spatial dimensions. Also where all the connectors come together at the PGBT bridge there is only a small area to complete all of the different elements of the direct connectors. Such as pouring concrete, placing beams with a crane, etc.

3.1.4.5 Lake Construction

The 1.0 mile long PGBT bridge crosses over Lake Ray Hubbard, which is a popular recreational lake. The 1.0 mile long bridge will require ~52 bents for each direction (north and south) with each bent having four columns and four drilled shafts. Working over and in water is more difficult than on land. One of the biggest reasons is special equipment such as barges must be used. Another reason is that all workers must be on something that can float, there is not the freedom to move where ever they please. Also, work is slower on water because it takes longer to move equipment and people on water. All of these issues are compounded because the lake is used for recreation. Special considerations have to be in place for the safety of the public and workers, such as a perimeter around the construction area. Work over water does not happen as often as work on land so it makes everything more complicated.

3.1.5 Analysis

In order to address some of the challenges discussed above this author, Gau (2009), and David Ortiz have been supporting TxDOT with construction analysis using 3D and 4D visualization. David Ortiz was the first to work on the project in early 2007, and he was the one to build the 3D model. As Gau reported in 2009, he did much of the analysis presented below. This author has continued to support TxDOT after Gau left.

3.1.5.1 ROW acquisition

The original reason for developing the 3D and 4D model of the project was to visually communicate to the NTTA how their right-of-way (ROW) parcel acquisition schedule would affect the TxDOT contractor. In order to accomplish this, the 3D model of the project elements was created in AutoCAD from the 90% plan set and electronic 2D CAD files. For the visual communication of the parcel acquisition, each parcel was modeled as a thin 3D object with different colors, as seen in Figure 3-22. Once both of the 3D models were complete, the 4D model was made by linking the 3D objects with the construction schedule and ROW acquisition schedule. The 4D model was able to show the project being built (appearing on screen) in the same platform the parcels were being acquired (disappearing from screen). This made it very easy to see if there was any time conflicts because there would be project elements on the screen the same time as parcels. As it turns out, there was a conflict between one of the parcels and a culvert as seen in Figure 3-23. The situation was rectified by altering the ROW acquisition schedule so the project could be completed on time.

Figure 3-22 3D Model of ROW Parcels and Existing Conditions (I-30, apartment complex, etc.)

In order to visually see the impact of the parcel acquisition schedule each parcel was modeled as a thin 3D object. Parcels were also given different colors to distinguish one from another.

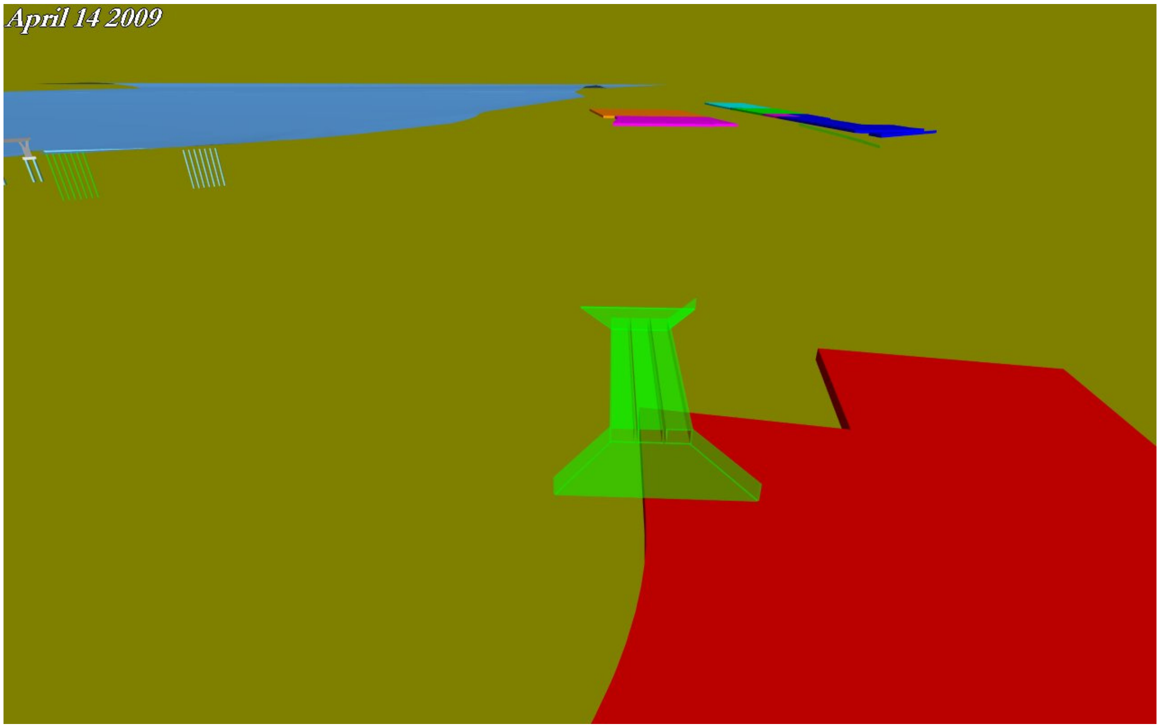

Figure 3-23 Conflict between Construction Schedule and ROW Acquisition Schedule (looking east)

Work on Culvert 3 is schedule to start (shown by green color) before the parcel (red) is acquired. Culvert 3 is schedule to start construction on April 14, 2009, while the parcel (26) will not be acquired until May 2, 2009. By that time culvert 3 is actually scheduled to be complete.

3.1.5.2 Utility Relocation

Utility relocation is often an issue with projects, and as discussed above it was one of the challenges for this project. Once the information was available, the existing utilities were added to the 4D model, much like the parcels were. Another reason they were added is because this project has a large amount of utilities that must be relocated. Just as with the parcel and culvert conflict, the 4D model makes it very easy to identify issues. After adding the utilities to the model, a manual review showed conflicts between existing utilities and new drilled shafts for direct connectors, as seen in Figure 3-24. The drilled shafts were schedule to be complete before the utilities were planned to be relocated. In order to keep the project on schedule the utility relocation schedule was altered to align with the construction schedule for the drilled shafts.

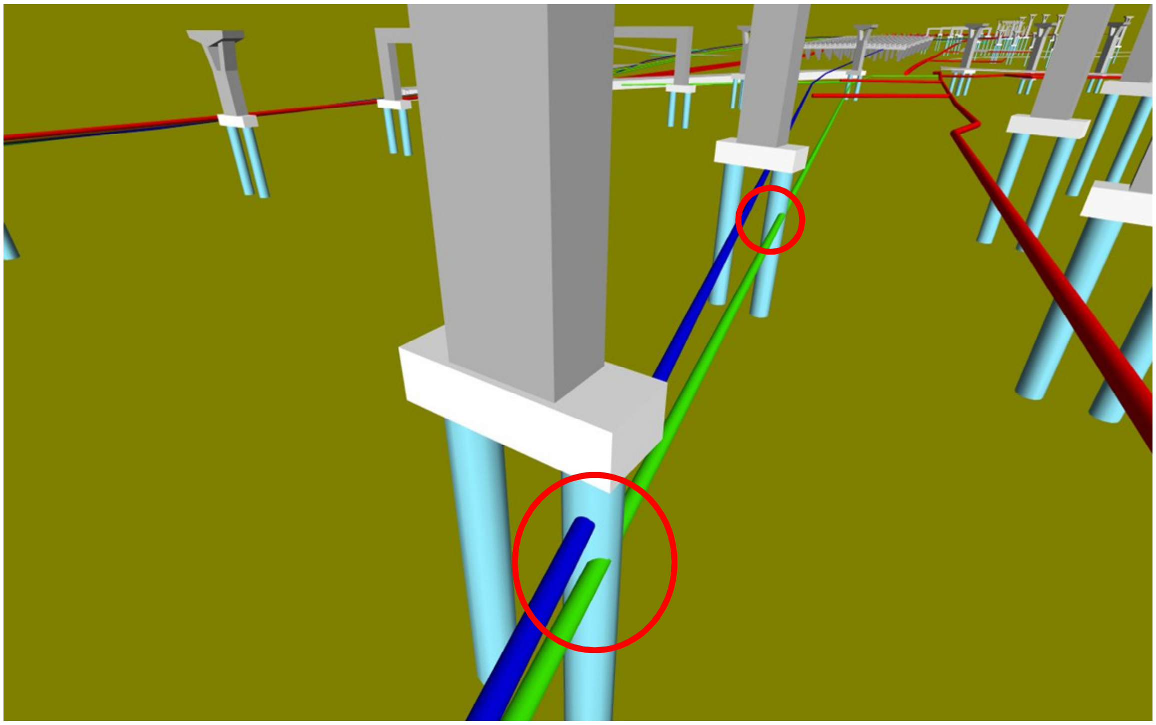

Figure 3-24 Space Conflict between Existing Utilities and New Drilled Shafts (circled in red)

Water lines (blue) and sanitary sewer lines (green) are not schedule to be moved in time for the drilled shafts of DC04 to be under construction.

3.1.5.3 TCP analysis

Before the schedule was complete the only sequencing information available to Gau was the traffic control plan (TCP). Therefore, rough 4D modeling was done with the information from the TCP and some educated assumptions. With the best 4D model possible, Gau was able to analyze the TCP. The first analysis he completed was checking the construction sequence of two of the direct connectors that cross over each other, as seen in Figure 3-25. Because the direct connectors cross each other the beams and deck of the lower one need to be complete before the higher one. If done in the opposite order there would not be enough clearance room to place the beams for the lower direct connector. The analysis confirms that construction is completed in the correct order. The other issue discovered is a potential safety issue with construction of a direct connector over open lanes of traffic as seen in Figure 3-26. The TCP calls for a direct connector to be under construction while lanes below are carrying traffic. This is a potential safety issue that should be investigated further because the TCP has very long phase durations. The long durations make it not possible to positively say there will be a safety issue. For example, the direct connector could finish construction before traffic is allowed on the road below, or the contractor is planning on closing that road while work is happening. There is simply not enough information from the TCP, so there needs to be further investigation of the issue with smaller duration intervals. The 3D model helped identify this issue as the 2D plans do not present the information that the direct connector crosses over the open traffic lane as well as the 3D model.

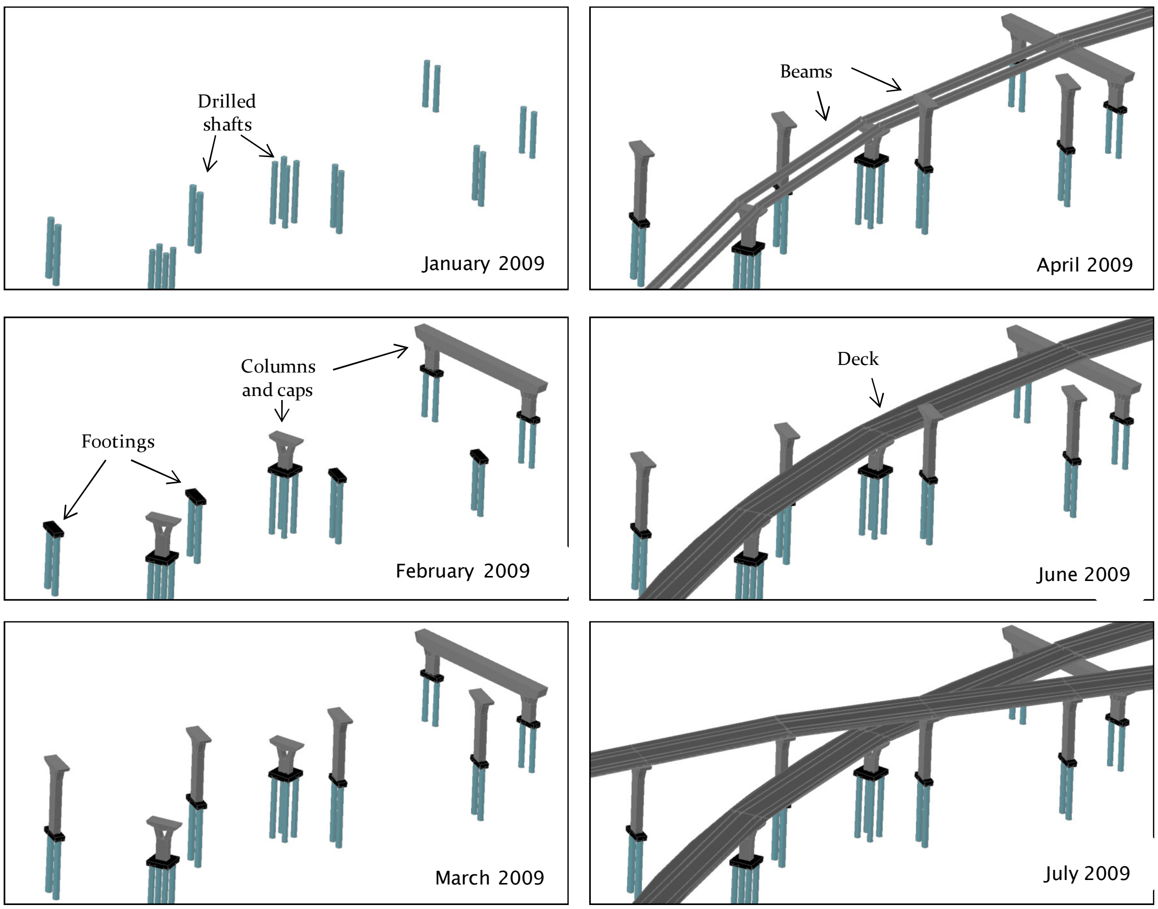

Figure 3-25 Construction Sequence of Two Direct Connectors That Cross Over Each Other

This simulation verifies construction sequence is correct as the beams and deck of lower direct connector are constructed before beams and deck of higher direct connector.

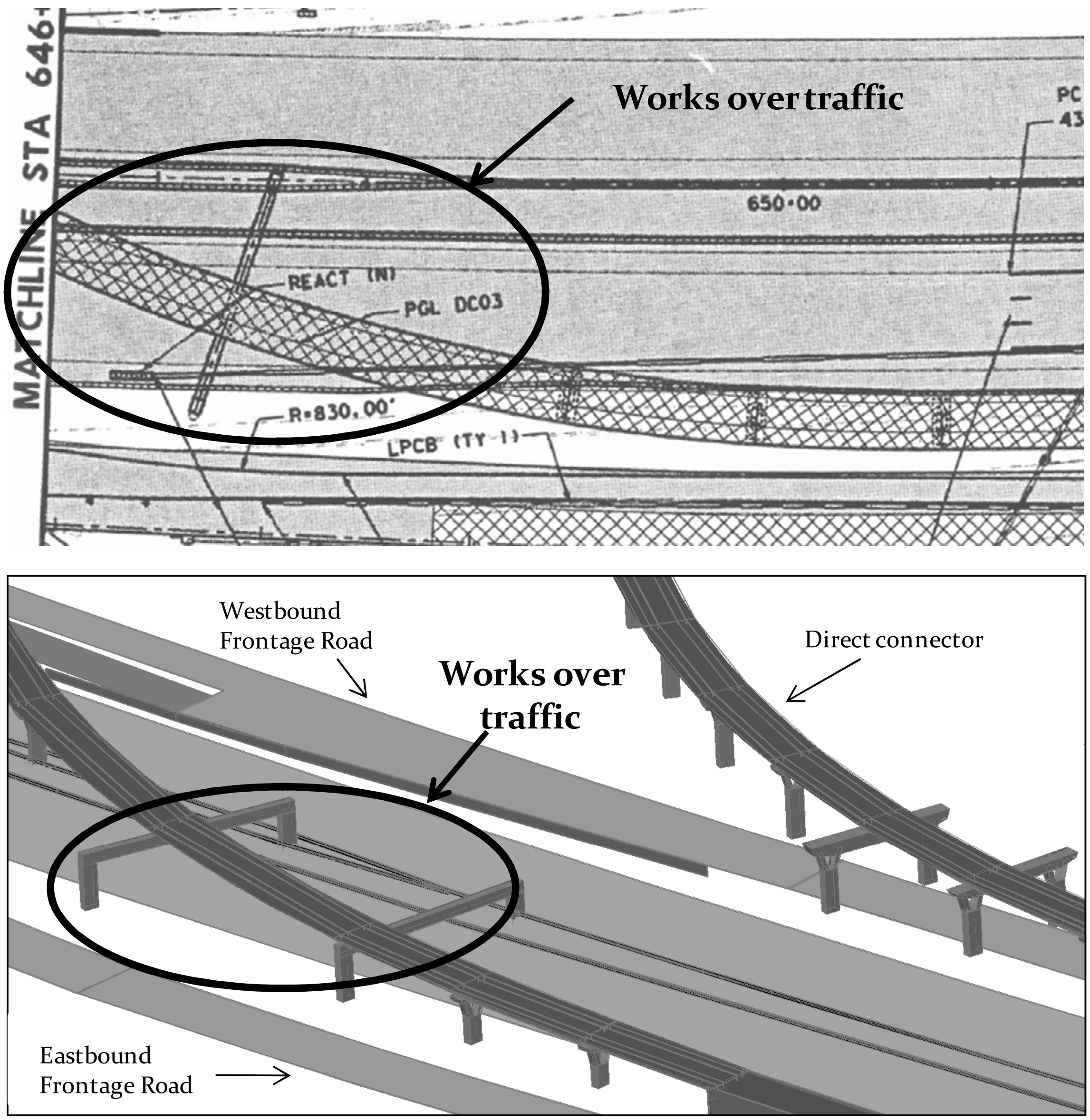

Figure 3-26 2D Plans (above) and 3D Model (below) Showing Potential Safety Issue (TxDOT, 2009)

The 2D TCP plan set shows potential construction happening over lanes open to traffic. A 3D model of the situation helped identify the issue because 3D provides more information than 2D.

The author of this thesis has continued to support TxDOT during the construction phase. Most frequently by updating the 4D model and checking for construction sequence issues. Although recently TxDOT has asked the author to help them to create a visualization that shows the impact of a communications utility being moved approximately 11 months behind schedule. That 11 month delay equates to approximately 6 months of total schedule delay. This visualization will be used during meetings to discuss solutions.

Gau and this author have supported the construction team with 3D and 4D analysis when issues came up. Ideally though, the issues would never have happened. Assisting the construction team on this project for the past two years with the work presented above has lead this author to believe that utilizing 3D and 4D visualization during the planning and design phases could have prevented these issues from happening, or at least given the designers a better chance to catch the errors before construction started. This claim is supported by the overwhelming amount of research that supports using constructability early in the planning process and continuing during all project phases, which was discussed in Chapter 2. Along with the issues presented above, this author has interviewed the TxDOT project manager about additional issues they have encountered on this project and their impacts. With the analysis from the previous two years of work that was presented above and the knowledge gained from the literature review, the author has developed specific ideas about how 3D and 4D visualization used throughout the entire design phase could have improved the issues that have come up during construction of this project. For the issues discussed below, each one has a detailed description as well the impact(s) the issue had on the project. For the proposed solutions the author presents how the literature has impacted this category of issue and then builds on the literature by adding the experience he has gained from the previous two years of work on this project. Also included is a scale for how much impact 3D and 4D modeling could have for the project. The scale is based on a combination of the impact the issue has on the project and the impact 3D/4D has on the issue. A **Large Impact** indicates the issue is significant and that 3D/4D could have a significant impact on the issue. A **Medium Impact** could be a combination of a large issue and small impact of 3D/4D on that issue, or vice versa, or both the issue and 3D/4D impact on that issue are medium. An **Indirect Impact** means the issue has a significant impact on the project, but the cause of the issue was related to construction; not design. Therefore, 3D/4D in the early design phase could not have prevented the issue, but using the 3D/4D developed during design can reduce the impact. Finally a **Potential Issue** is an issue that has not had a significant impact, but the conditions are ripe for it and that 3D/4D in the early design phase could have potentially prevented it. All of the issues are summarized at the end in Table 3-1 Summary of Issues for PGBT for easy review.

3.1.6 Issues

3.1.6.1 Drainage Phasing

The TCP, which also dictates construction phasing, specified the existing drainage system on the east side of I-30 to be demolished before the new systems was in place without a temporary system planned for. This creates an issue because between the time when the old system is demolished and the new system is complete there will not be a system to control the water runoff. The error was caught in the early phases of construction where TxDOT and the contractor could re-sequence some of the work without any cost of schedule impacts. Had the error not been caught until late, there could have been a major cost component to put in a temporary system or flooding of the area which would could delay construction and potentially cause safety issues for drivers.

This issue deals with need to visualize the schedule so more information is available to catch errors. When building the 4D model it encourages interaction between the designer, planner, and builder (Koo and Fischer, 2000). Koo and Fischer, (2000) also found that as a visualization tool, 3D and 4D models "obviate the need to conceptualize the association between components and activities to comprehend the schedule…also [the models] show the spatial constraints between components, enabling users to detect space-related conflicts". On their case study, which analyzed a small office building with a 4D model, they found that the overhead HVAC system for the 2nd floor was scheduled before the 2nd floor slab and truss were completed, thus there was no platform for the contractors to work on. Also the roof was not completed either so there would have been no support for the HVAC to hang from.

The synthesis of information in 3D and 4D models could have provided the design team a better opportunity to discover their mistake than using 2D drawings. Also, while building the 3D and 4D models a lot of thought has to go into how all the components of the project interact and the order in which they get built. Going through that process would have given the design team even more of an opportunity to catch this error as well as other similar errors. 3D/4D early could have a **Medium Impact**.

3.1.6.2 Communications Utility

The relocation of a communications utility under the EBFR of I-30 was delayed 11 months. According to the TxDOT project manager the owner of the utility continuously dragged their feet to get started. Then after hiring a contractor to do the work, they changed their design. Also, at one point, they cut over the wrong lines and it took some time to decide how to fix that issue. In January 2010, the estimated completion was schedule for June 2010, but kept continually being pushed out until they actually finished at the beginning of January 2011. During the relocation activities, the contractor would update the estimated project completion conditioned upon an assumed date for the utility's completion. As such, the project completion date was pushed out several times during the work. The total schedule delay was 6 months after re-sequencing work around the relocation. Currently TxDOT and NTTA are discussing whether to accelerate the remaining work which will add cost. The major concern is that the project is a part of the eastern extension of the President George Bush Turnpike which has a firm date of being open, as dictated in the bonds used to build the corridor. The other part of the corridor is on schedule to open in time, but the connection with I-30 (this project) is the keystone of the corridor. Having the rest of the corridor open, without this section, does not provide much benefit to the public.

Utility conflicts are one of the most frequent issues on roadway construction project. According to Chong et al. 2005; Ellis and Thomas 2002, utility conflicts are one of the most significant and frequent sources of construction delays on United States roadway projects. As an indication regarding the frequency of utility conflicts, a report by the United States General Accounting Office (USGAO 1999) showed that 22 out of the

44 states surveyed in the research reported utility delays on at least 11% of the projects within their state. To help with utilities issues 4D models are able to show "spatial constraints on the site and in the building which allows users to verify whether a component can be physically placed or where crew can work in a certain location" (Koo and Fisher, 2000).

The cause of this is issue is not related to design or planning, so utilizing 3D and 4D during those phases of the project would not have stopped the utility owner from dragging their feet. The only way 3D/4D modeling could have helped in the early design phases is by modeling all the existing utilities in the area, so utility information could be part of the alignment selection criteria. For this issue specifically though, the 3D and 4D models developed during the design phase could have been used while this issue was taking place to increase communication, help facilitate meetings, and evaluate different solutions. The literature reviews supports that facilitating communication is one of the major benefits of 3D and 4D visualization. Nothing in the design phase would have changed by using 3D and 4D models, but the 3D/4D model that was created during the design phase could also benefit all the parties involved in this issue (TxDOT, the contractor, utility company, etc.). 3D/4D early could have made an **Indirect Impact**.

3.1.6.3 Traffic Control Plan

The original TCP issued had six phases where traffic on I-30 was shifted laterally in small amounts. After reviewing the plans the contractor suggested that the project could be completed with fewer, but more dramatic traffic shifts. This saved a total of $210,188 and also regained 53 days of delay due to utility relocation along the I-30 WBFR. It also created a safer work zone by separating construction traffic and roadway traffic, such as hauling materials and equipment.

This issue deals with need to analyze construction sequencing as well as traffic planning. Koo and Fischer, (2000) found 4D CAD could be used to "detect potential site logistical challenges and accessibility problems". The 4D model they created help them identify a scheduling issue. The proposed schedule had one set of stairs installed early to allow access to the 2nd floor. However, when access was needed to the stairs other work was going on that limited access. The second set of stairs was not scheduled to be complete until after the work blocking the first set of stairs was clear. This meant there was a possible delay to work on the 2nd floor. For this case study, the easy visualization of space in a 4D model was what lead to the discovery of the issue. To integrate traffic planning into the construction sequencing model Liapi, (2003) made "lane indications graphical objects that are represented with activities added to the schedule" (Liapi et al., 2003). That way the "4D model can be of value to traffic engineers and contractor" (Liapi et al., 2003).

A 4D simulation of traffic and construction could have been used to analyze different versions of the TCP so the optimum one could be selected. Had a different TCP been in the plans, the bids might have been lower which would save TxDOT money. 3D/4D early could have made a **Medium Impact**.

3.1.6.4 Right-of-Way Acquisition

NTTA is acquiring all the ROW for the entire Eastern Extension Project, including the section TxDOT is completing. In order to complete the project the construction schedule is running very close to the acquisition schedule. As discussed above there was a conflict between the two schedules that eventually got resolved.

This issue deals with time-space conflicts as well as coordination. Both of which 3D/4D modeling can be beneficial for. Koo and Fischer, (2000) found on their case study, which analyzed a small office building with a 4D model, "that the overhead HVAC system for the 2nd floor was scheduled before the 2nd floor slab and truss were completed, thus there was no platform for the contractors to work on. Also the roof was not completed either so there would have been no support for the HVAC to hang from. For communication Hartmann and Fischer, (2008) created 3D/4D visualization models to support constructability reviews on a major subway reconstruction project in New York City (NYC). The project team in NYC decided to build a 3D/4D model of the project to "support, visually, the communication between numerous stakeholders of the project". The models were used during design review meetings, to generate drawings for communicating design issues. With these 3D and 4D models "the project team could communicate product and process knowledge more efficiently". For transportation construction, Kim et al. (2011) found 4D models were "quite helpful for the smooth execution for the project especially in the area of communication management". The engineers for the contractor could easily communicate with the engineers for the subcontractors" (Kim et al., 2011). Also, "The model helped construction managers and engineers visualize and better estimate the whole construction scenario" (Kim et al., 2011).

The 4D model created for this schedule was the tool that helped identify this issue. The synthesis of information in a single platform (4D model) was the key to the discovery. If the designers and planner knew ROW acquisition was going to be an issue, a model similar to the one Gau (2009) created could have been created so this issue could have been identified earlier. 3D and 4D modeling could have a **Small Impact**.

3.1.6.5 Alignment Selection

The alignment selected for this project created several issues that were very expensive. The cost of acquisition included an apartment complex, several houses, and other areas. Also the route selected to cross the lake is one of the longer routes available (1.0 mile), which means more money had to be spent to construct a longer bridge over the lake and make the connection with I-30 compared to a shorter bridge. The last issue is that this area had a large amount of utility relocation required. The literature review shows that utility relocation is one of the biggest issues and is encountered on a large percentage of projects.

This issue deals with the need for evaluating design alternatives. Ganah, et al. (2005) found that "3-D modeling helps in identifying any missing information for building a particular component" and that "by modeling design details [in 3D], decisions can be made on the design and the results can be seen before the construction start". For transportation Liapi et al., (2003) used her 4D model to get "effective feedback in terms of alternative schedules and allowed TxDOT personnel to make better decisions". Specifically, "the early construction of an overpass was identified by TxDOT engineers as a potential problem in the proposed contractor's schedule" (Liapi et al., 2003).

The synthesis of information available in 3D and 4D models could have helped evaluate project tradeoffs early in the project development phase. More information would have been available, so hopefully the best (defined by project stakeholders) solution could have been implemented. The size and complexity of this project makes it hard to evaluate all the different tradeoffs in someone's head, so modeling could be a tool that helps present all the issues in a single medium. 3D/4D early could have a **Medium Impact.**

Table 3-1 Summary of Issues for PGBT

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Drainage Phasing	The TCP called for the existing drainage system on the east side of I-30 be demolished before the new system is complete. The time period between when the old system was demolished and the new system is complete there will be no system to handle the water runoff.	**Medium Impact** - The synthesis of information in a very visual way as well as the thought about how all the components of the project interact and the process in which they get built required when creating the 3D and 4D model gives the design team a better opportunity to catch this error as well as other similar errors. Koo and Fischer (2000 comment "when building the 4D model it encourages interaction between the designer, planner, and builder."	Synthesis of information	The drainage system would need to be model, as well as a rough TCP developed.
Communications Utility	A communications utility under the EBFR was relocated 11 months later than planned. The owner of the utility continuously dragged their feet to get started. Then after hiring a contractor to do the work, they changed their design. Also, at one point, they cut over the wrong lines and it took some time to decide how to handle that.	**Indirect Impact** - According to Chong et al. 2005; Ellis and Thomas 2002, utility conflicts are one of the most significant and frequent sources of construction delays on United States roadway projects. The only way 3D/4D modeling could have helped in the early design phases is by modeling all the existing utilities in the area so utilities information could be part of the alignment selection criteria. For this issue specifically though, the 3D and 4D models developed during the design phase could have been used while this issue was taking place to increase communication and help facilitate meetings, and evaluating different solutions.	Increased Communication	To assist with alignment selection all the utilities in the area would need to be modeled. Not as precise as for space conflict detection, but so that one can get a general sense of the amount of utilities in an area.

Table 3-1, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Traffic Control Plan	The traffic control plan in the initial issue of plans required a high number of traffic shifts.	**Medium Impact** - A 4D simulation of traffic and construction as Liapi (2003) used could have helped analyze different versions of the TCP so the optimum one could be selected. This would have potentially allowed for lower bids on the project.	Simulation of construction	The new design of the highway and the temporary roadways would need to be model. Ideally as the TCP developed in detail the 3D and 4D model would as well so analysis could be done at all phases
ROW Acquisition Schedule	NTTA is acquiring the parcels for TxDOT's portion of construction for the project. The parcel acquisition schedule was not coordinated with TxDOT's construction schedule so it was discovered that the construction schedule planned work on parcels that were not planned to be acquired.	**Small Impact** - 3D and 4D models could have been used to help with interface and coordination meetings throughout the design and planning process. Hartmann and Fischer, (2008) used 3D and 4D models on a subway reconstruction project in New York City to communicate product and process knowledge more efficiently The synthesis of information in one medium (3D/4D model) could present issues not thought to be present.	Synthesis of information, Coordination and integration of different parties	A rough schedule and a complete 3D model need to be developed. Also the schedule of parcel acquisition as well as the map of the parcels to be acquired needs to be available

Table 3–1, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Alignment Selection	The alignment selected for this project created several issues that were very expensive. The cost of acquisition included an apartment complex, several houses, and other areas. Also the route selected to cross the lake is one of the longer routes available (1.0 mile). The last issue is that this area had a large amount of utility relocation required.	**Medium Impact** - The synthesis of information available in 3D and 4D models could have helped evaluate project tradeoffs early in the project development phase. Ganah, et al. (2005) found "by modeling design details [in 3D], decisions can be made on the design. More information would have been available, so hopefully the best (defined by project stakeholders) solution could have been implemented.	Design alternative check	At this early in the project phase a rough model would help to provide more information than is usually considered. The model can then be refined to help with quantities, etc.

3.2 Woodall Rodgers Deck Plaza

3.2.1 Introduction

The Woodall Rodgers Deck Plaza is a beautification and renewal construction project in Dallas, TX. The end result of the project is the creation of a 5.2 acre park that will serve as a "central gathering space for Dallas and its visitors to enjoy the heart of the city", as seen in Figure 3-27. "The park will promote increased pedestrian, trolley and bicycle use between Uptown, Downtown and the Arts district" (The Park, 2011). The park is being constructed over 1,200 linear feet of the existing SH-366/Woodall Rogers eight total lane highway in downtown Dallas as seen in Figure 3-28. TxDOT is responsible for a considerable amount of the project scope, but the project is only meant to create the park, not benefit the traveling public. The bid for the TxDOT scope was $44.5 MN with $16.7 MN in American Recovery and Reinvestment Act (ARRA) funds. Work began in October 2009 and at the time of this writing is scheduled to be substantially complete April 2012, which is 3 months delayed from the contract date.

Figure 3-27 Woodall Rodgers Park Rendering – looking northeast (The Park, 2011)

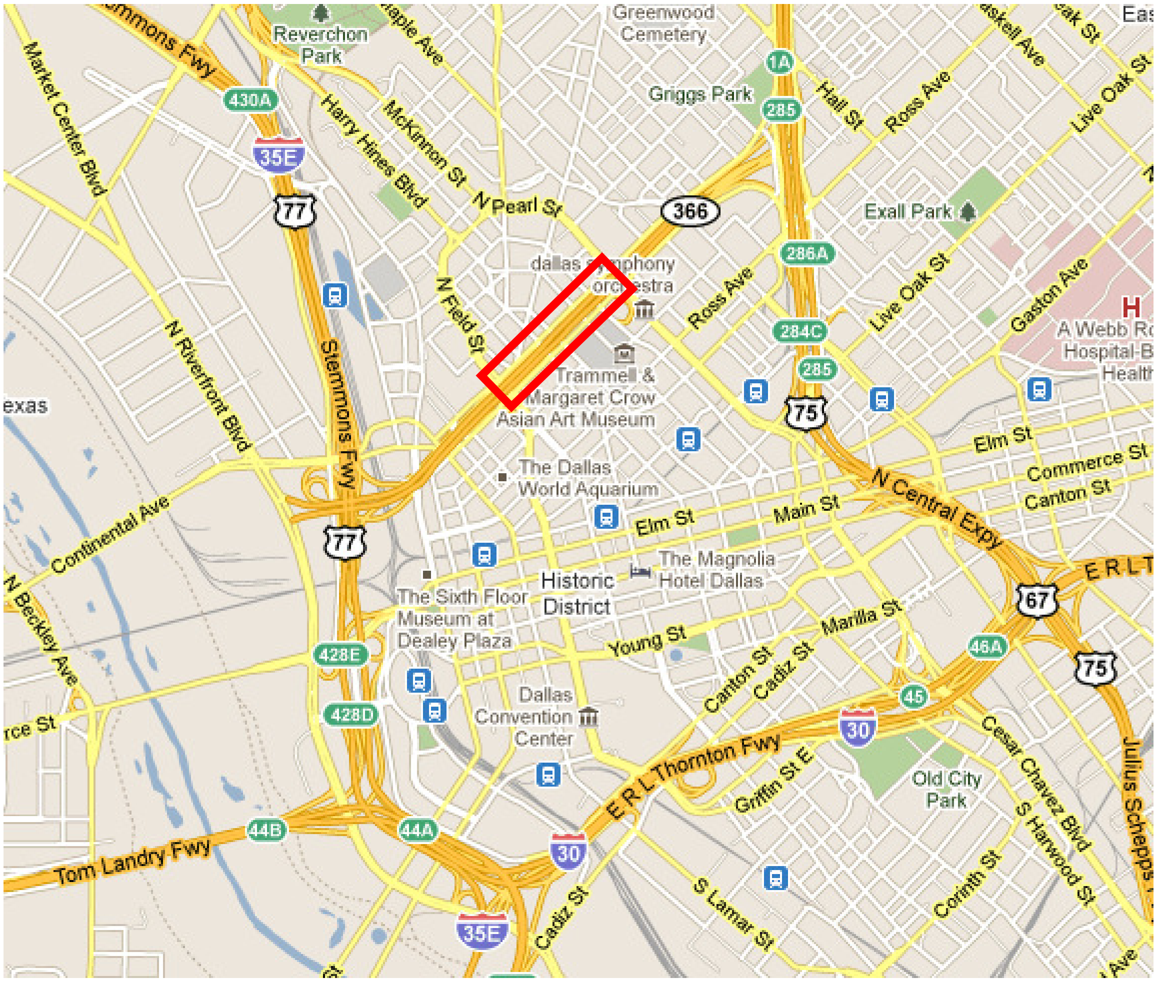

Figure 3-28 Project Location in Downtown Dallas – Outlined In Red (Google Maps, 2011)

3.2.2 Project Orientation

The existing highway main lanes are sunk below the surrounding area, while the frontage roads for the highway are at the same elevated level as all the buildings and streets in the surrounding area as seen in Figure 3-29. There are also cross streets with bridges over the highway. Two create the eastern (Pearl St.) and western (St. Paul St.) border of the project, while two others cross within the project boundaries. One will be demolished (Harwood St.) with one remaining as a divide in the park (Olive St.). There are also two utility bridges that cross the highway that carry communication lines for a very important client.

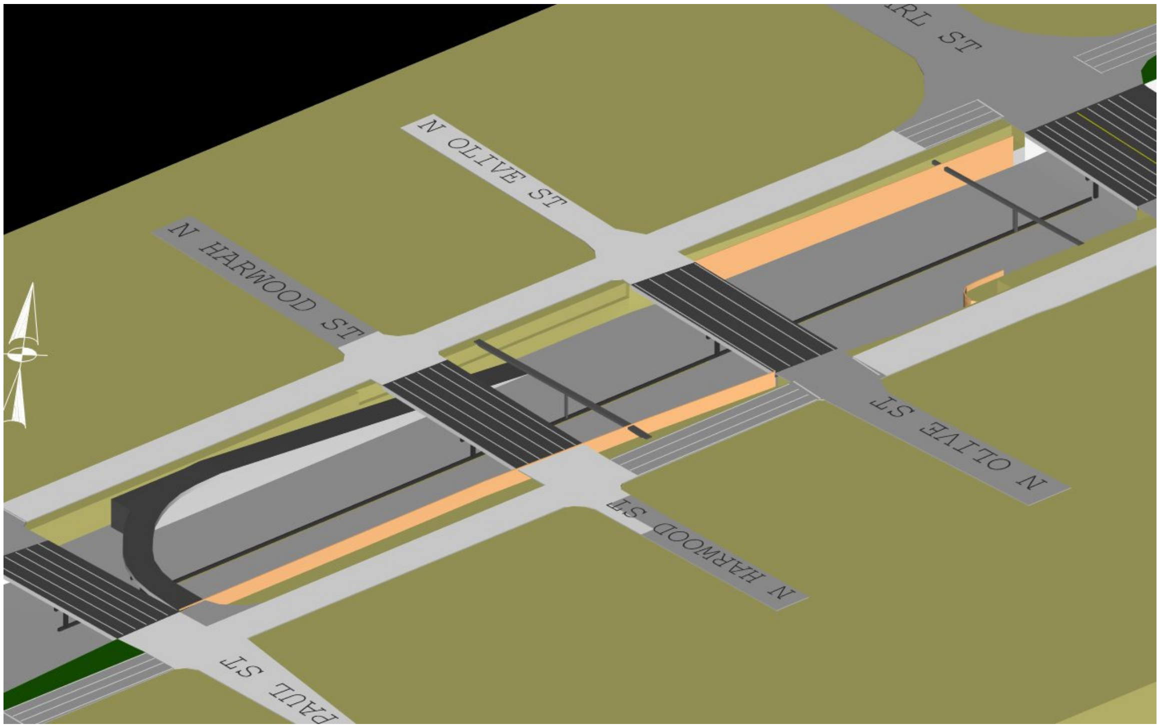

Figure 3-29 Woodall Deck Plaza - Before Construction

3.2.3 Scope

The park will have several amenities such as a restaurant, gardens, fountains, dog park, open lawn, and performance stage. The end result of TxDOT's scope will be the creation of the elevated flat surface for the park with soil and utility hook ups. Another contractor will finish all the park amenities. A more detailed list of items that are required to create the flat surface for the park is presented below. Figure 3-30 through Figure 3-37 present a photo sequence of the major portions of TxDOT's scope in roughly the order they must be accomplished.

Demolition

- Cross street (Harwood) – more room for park
- Utility bridges – space conflict with new beams, contents relocated to trench panels
- Top of retaining walls – space needed for abutments
- St. Paul St. exit ramp – ramp to be re-built with new configuration for beams
- Traffic signals – need to be replaced due to street demolitions and ramp reconfiguration

Construction

- Center bent wall and footing – support deck beams
- Masonry wall – under existing bridges between columns for fire protection
- St. Paul exit ramp – reconfigured
- Traffic signals
- Retaining walls
    - Drilled shafts (45)
- Abutments – support deck beams
    - Drilled shafts (210)
- Street parking - people using park
- Utilities
    - Electrical - vaults (3),
    - Gas
    - Water
    - Sanitary sewer
    - Control room
- Life safety systems – required because park creates a tunnel
    - Ventilation – jet fans
    - Fire line
    - Lighting – including emergency
    - Compressed air – for fire lines

- Pre-stressed box beams – 315, support deck
- Trench panels – 99, run utilities, provide additional depth for trees
- Deck slab – cast in place concrete, ties all beams together to provide stability
    - Waterproofing
    - Fireproofing
- Fill – flat surface for park amenities
- Landscaping – irrigation, trees

Begin Photo Sequence of Work

(all photo have same viewpoint – looking north)

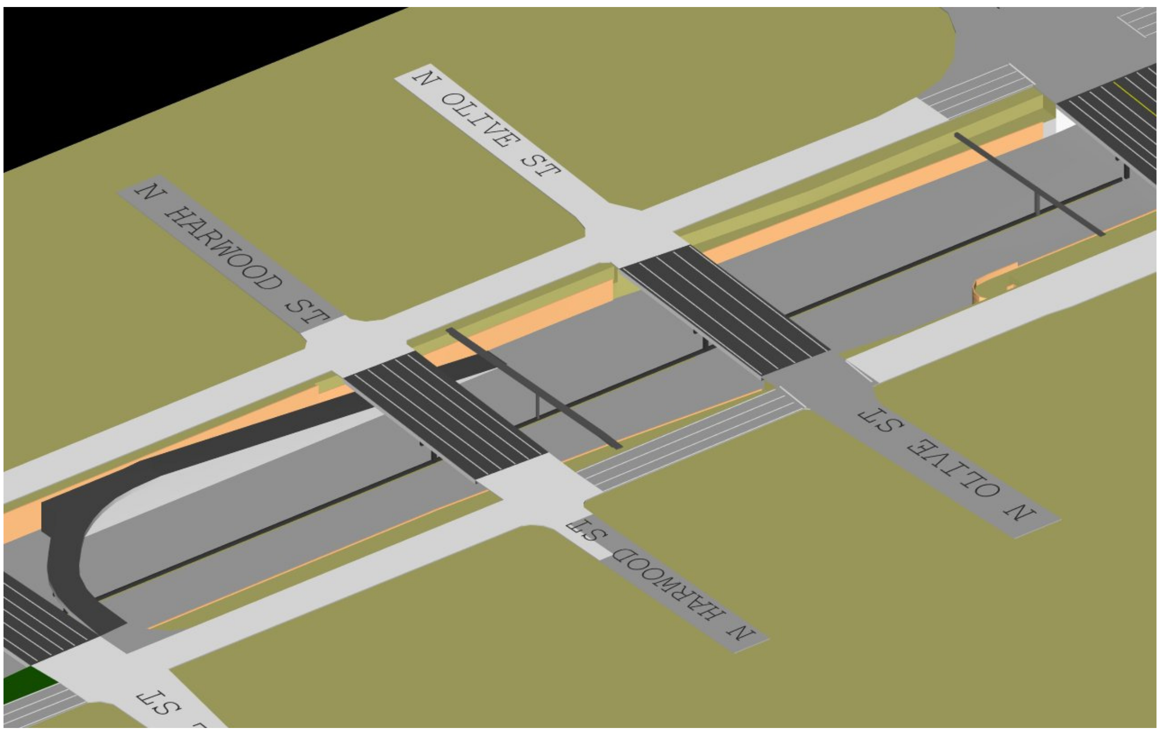

Figure 3-30 Existing Conditions

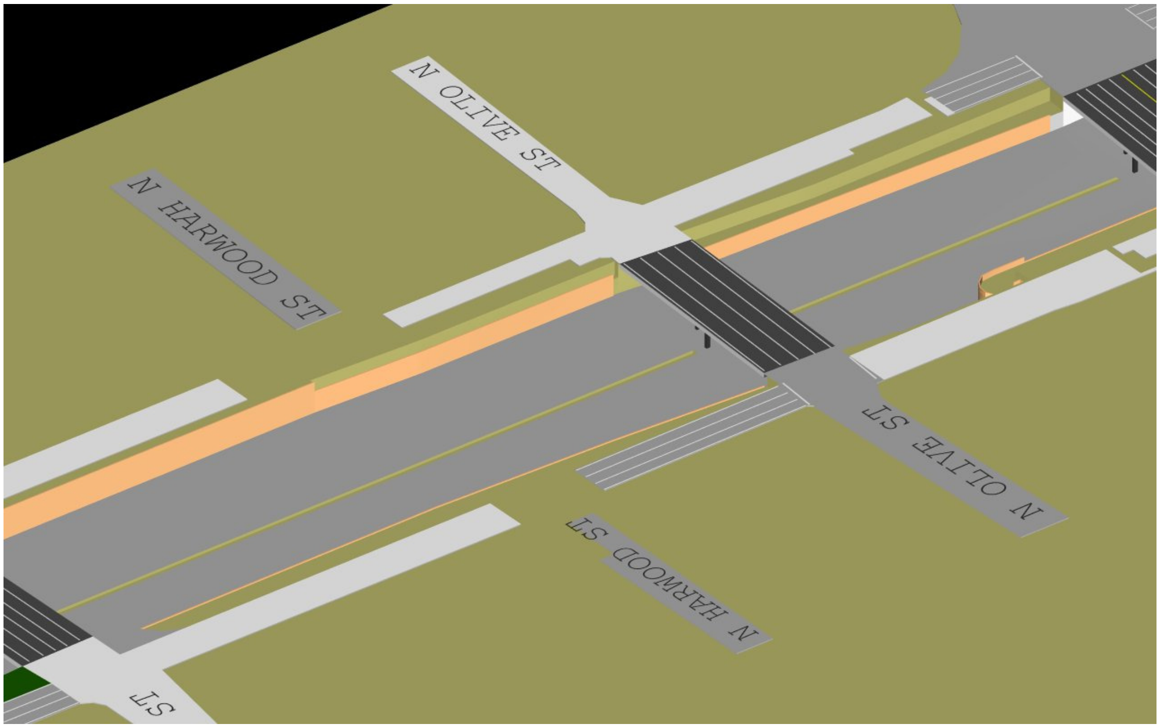

Figure 3-31 Demolition

Items to be demolished are: cross street bridge (Harwood), 2 utility bridges, St. Paul exit ramp, center traffic barrier, top of several retaining walls, EBFR and WBFR pavement sections

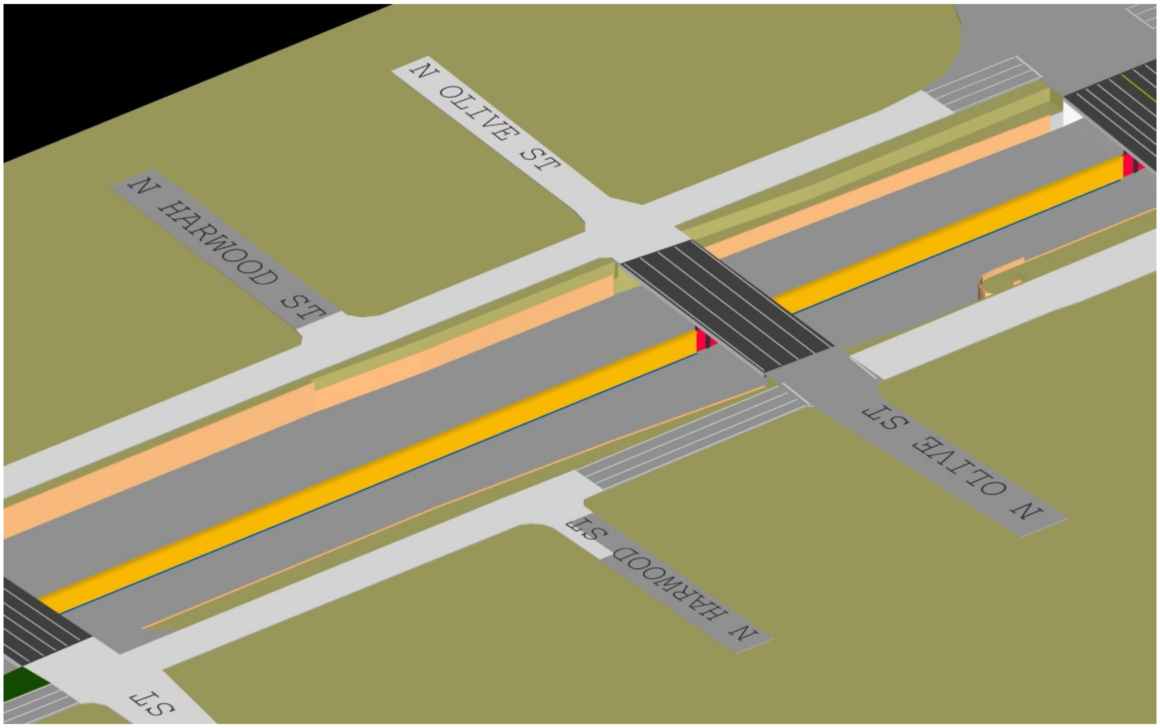

Figure 3-32 Construction of Center Bent Wall and Frontage Road Pavement

Traffic is shifted outward toward the frontage roads, and 1 lane on each side of the divide is closed for construction of the continuous center wall which provides support for the pre-stressed beams. Under the bridges masonry walls are built to provide a continuous fire barrier between the two different directions of traffic. Also, new Harwood St. pavement, EBFR and WBFR pavement is poured since those areas had to be reconfigured.

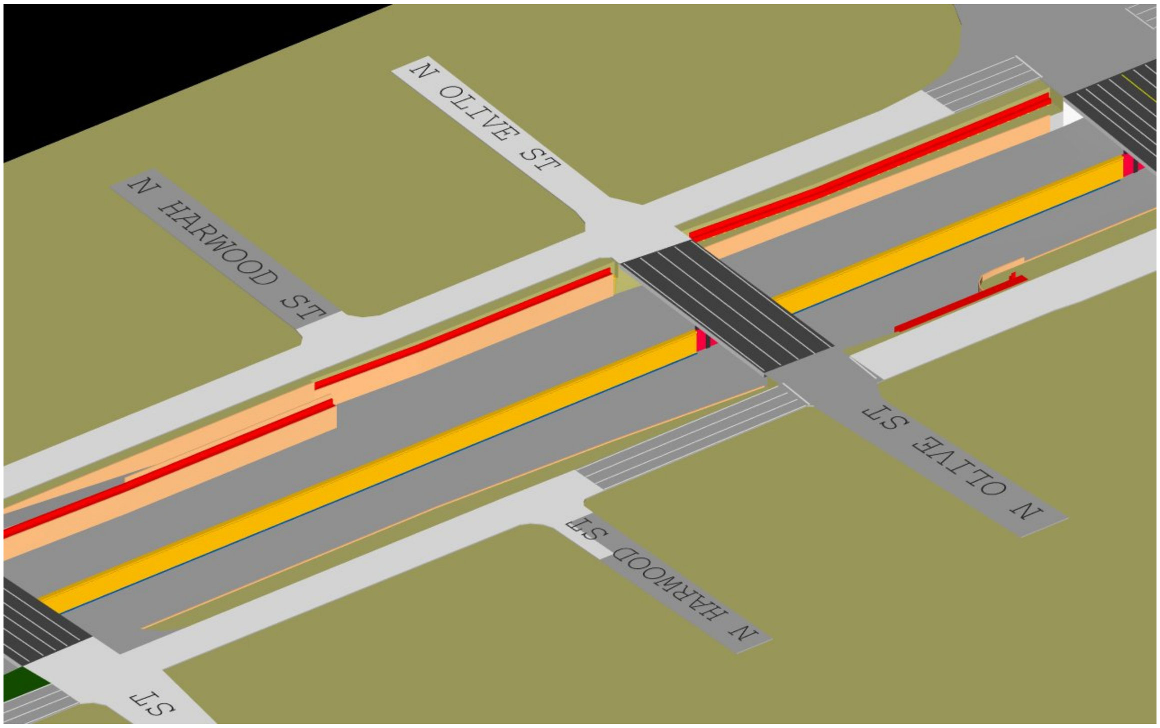

Figure 3-33 Construction of Abutments and Retaining Walls

After the center wall is built traffic is shifted inward toward the center wall and the outer most lane on each side is closed for construction of 9 retaining walls and 7 abutments. The abutments are the outer support for the pre-stressed beams. Also, the St. Paul exit ramp is reconstructed in its new configuration.

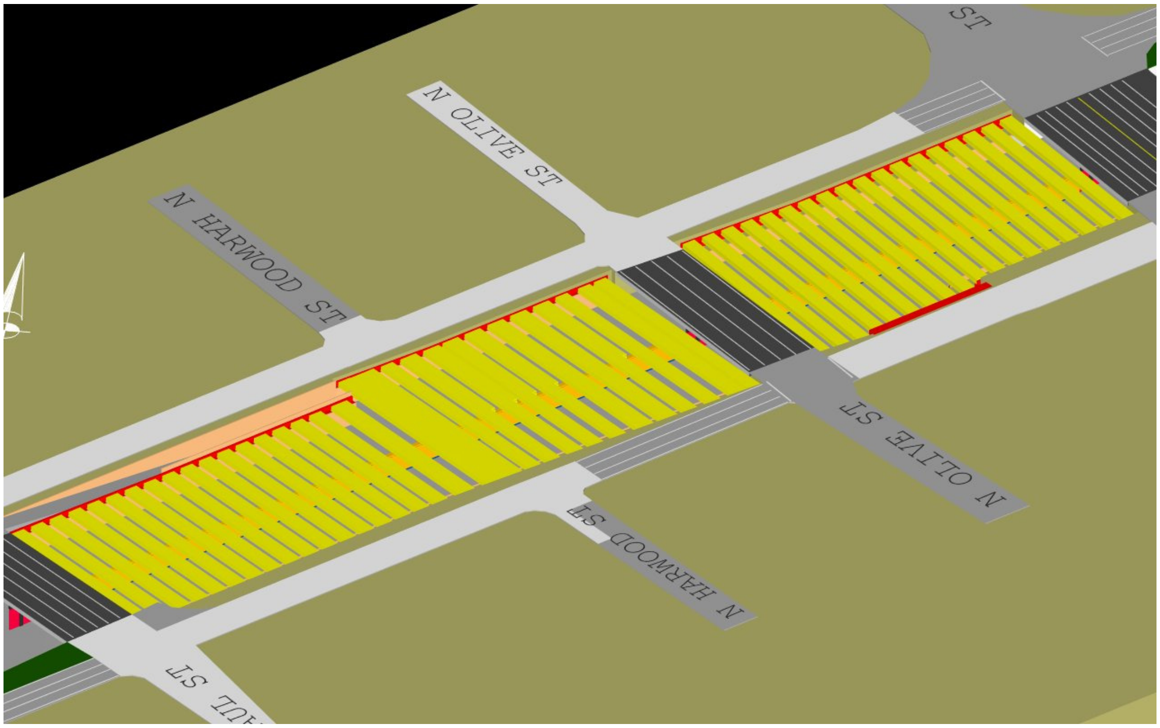

Figure 3-34 Placement of Pre-Stressed Box Beams (Yellow)

Placement of the 315 pre-stressed box beams is done in ~12 smaller sections as it can only be done on the weekends. This is because all the main lanes for the span with beams being placed must be closed for safety reasons.

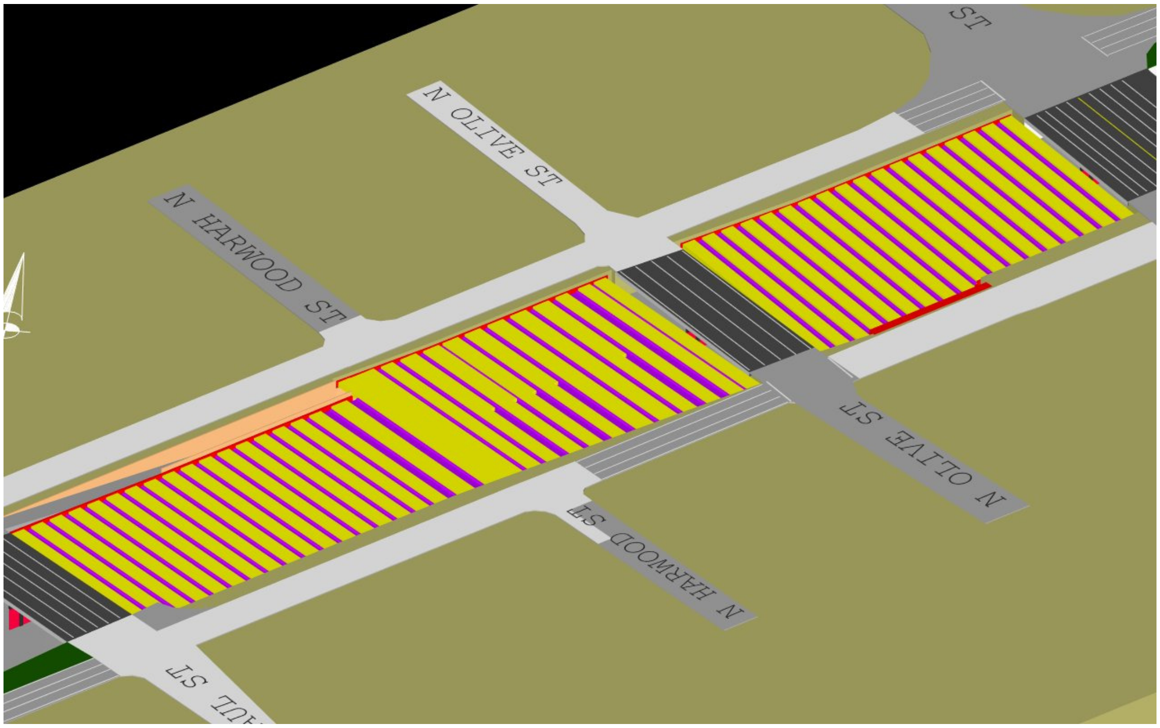

Figure 3-35 Placement Trench Panels (Purple)

Placement of 99 trench panels happens directly after the beams are placed in the same sections as beam placement (not all together after all the beams are placed). The trench panels are not as deep as the beams and therefore provide more room under the park for the park utilities to be routed as well as a place to plant the trees. The trench panels are supported by the beams along their entire length as seen in Figure 3-38

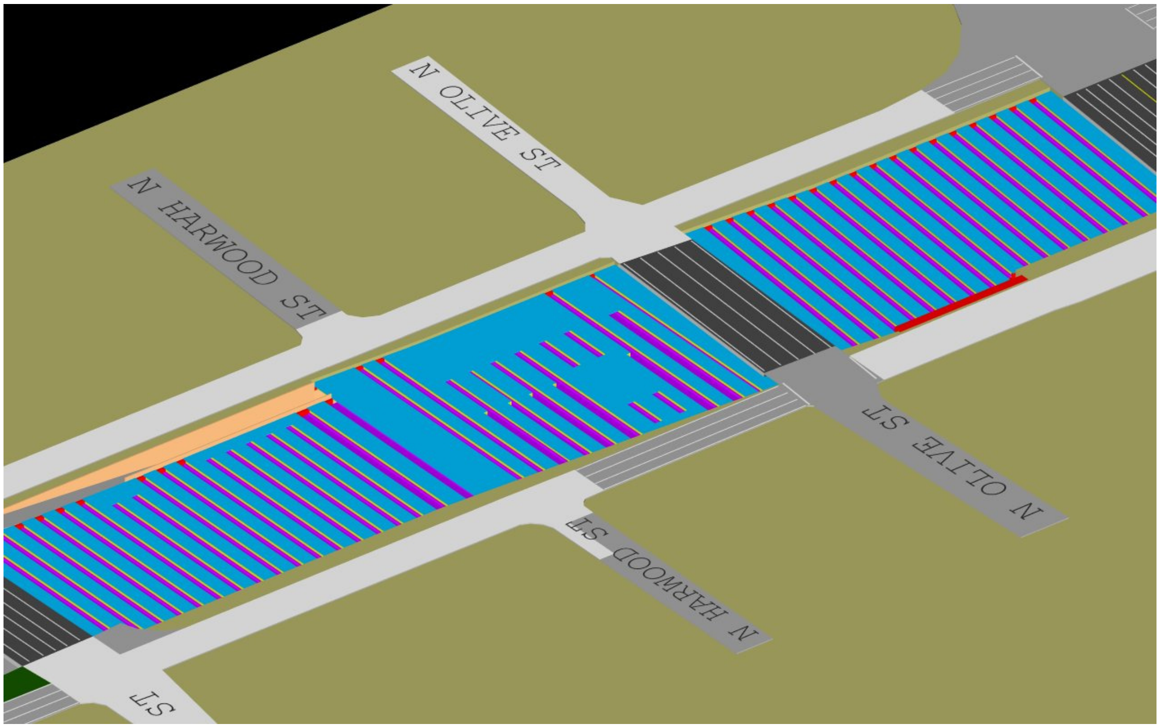

Figure 3-36 Construction of Deck Slabs (Blue)

Deck slabs are cast-in-place concrete that provide stability and strength for the deck by tying all the beams together. The deck slab construction also follows the same sections as the pre-stressed beams and trench panels.

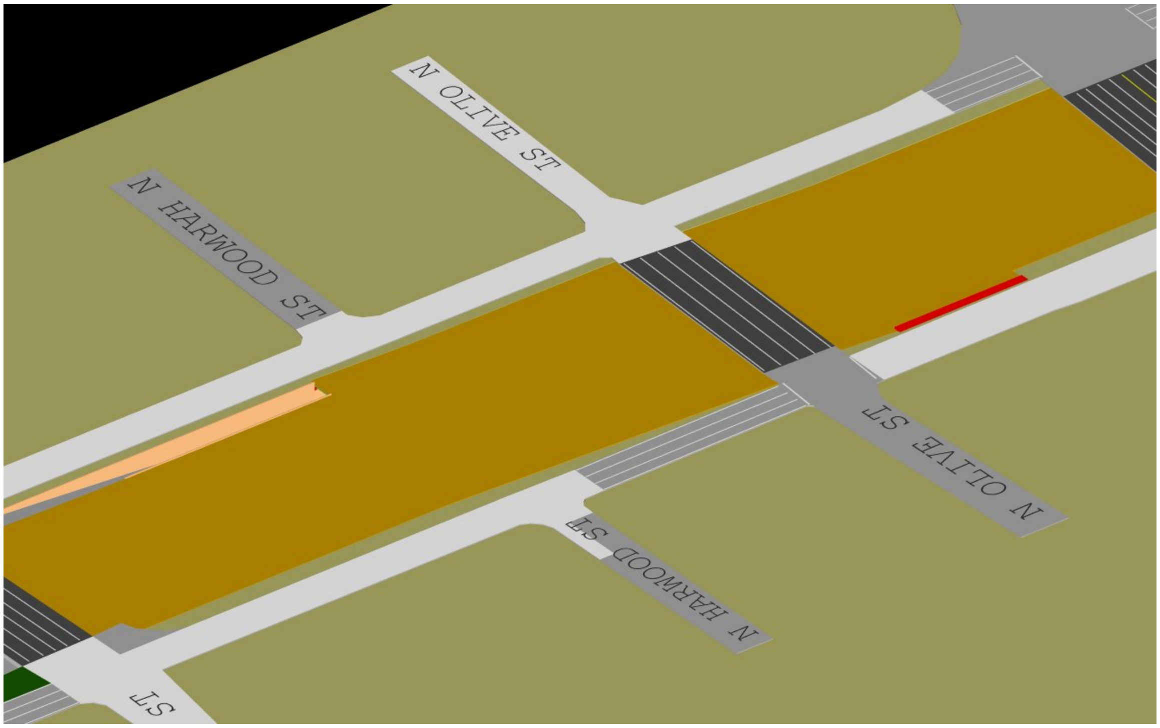

Figure 3-37 Construction of Park Fill, Irrigation, and Some Landscaping

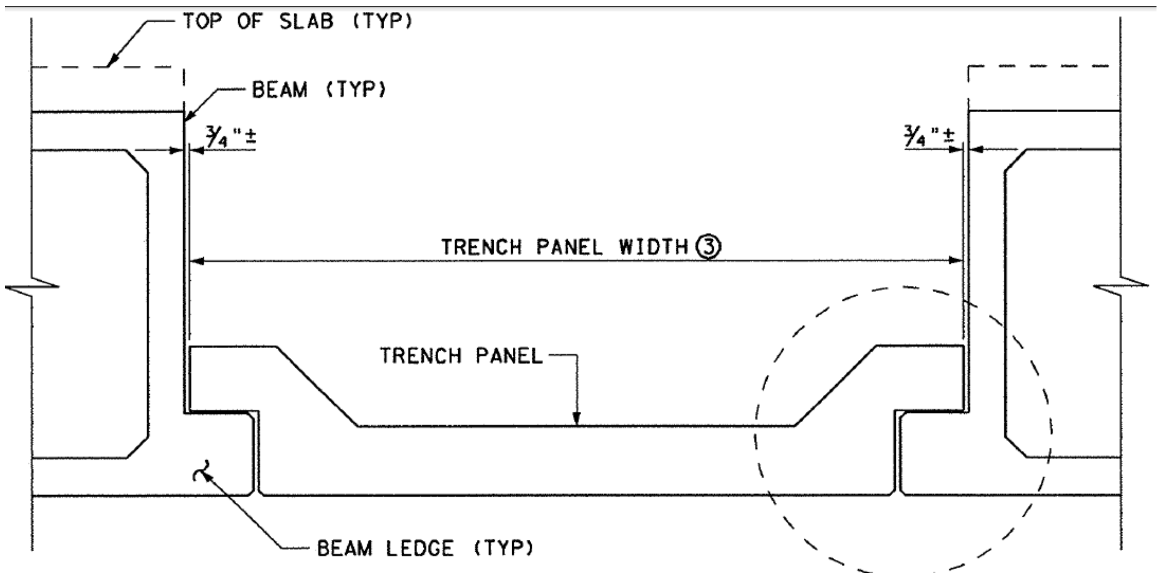

Figure 3-38 Section View of Deck That Will Support Park (construction plans)

The trench panel is a thinner, precast concrete member not meant to provide much support. It allows for trees to be planted and utilities to be run underneath the park. The trench panel is supported along its entire length by a ledge on the beams. Also notice the slab covering the beams in the upper left corner does not extend to the trench panel.

3.2.4 Challenges

3.2.4.1 Location – downtown Dallas

This project has several aspects that make it challenging to complete. The first is that project is located in downtown Dallas. Therefore there is a large amount of traffic that needs to be accommodated. This limits the amount of lane closures during peak traffic times. Also due to the project's location several community events restrict lane closures such as the State Fair of Texas, Super Bowl XLV week, holiday shopping, and the grand opening at the Dallas Opera. Exit ramp closures are also limited due to the amount of traffic on the road and location. The St. Paul exit ramp has to be demolished and re-built within 6 months. The Pearl St. exit ramp can only be closed for 4 months to build the straddle abutment that spans across the ramp, as seen in Figure 3-39. The Pearl St. exit ramp is the main exit for the State Fair, so no work on the straddle abutment could happen during the time the fair was taking place. The straddle abutment over the Pearl St. exit ramp requires a complicated construction procedure because it is post-tensioned. After the concrete has cured enough to remove the forms half of the tendons are post-tensioned, support is placed under the abutment, then the beams are placed on the abutment, then the last half of the tendons are post-tensioned, and the support is removed. All of this must be done in the 4 months allotted.

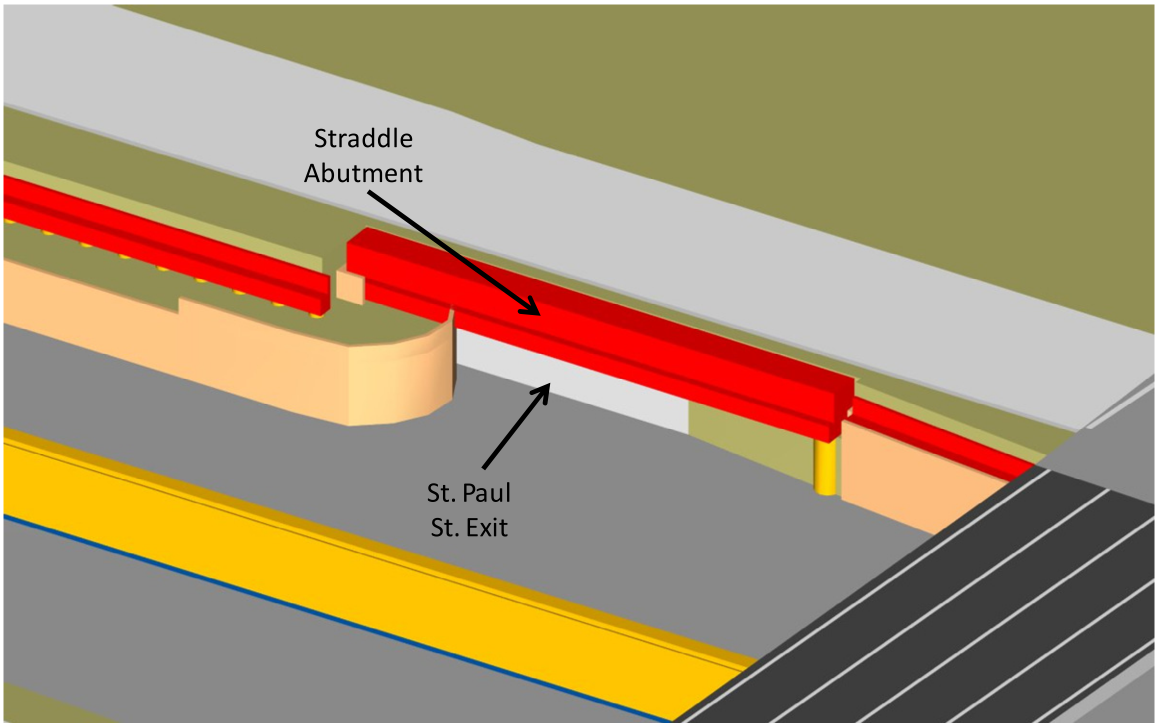

Figure 3-39 Abutment (Straddle) That Spans the Pearl St. Exit Ramp. (looking southeast)

The abutment is 126 ft long and 11.5 ft deep so it has to be post-tensioned. Due to the heavy load of the beams it will hold, there is a special sequence for post-tensioning. Half of the tendons are post-tensioned, support is placed under the abutment, then the beams are placed on the abutment, then the last half of the tendons are post-tensioned, and the support is removed. All of this must be done in the 4 months allotted.

3.2.4.2 Beams

The pre-stressed beams used to support the park are very large and weigh a great deal. The lengths range from 75 ft to 105 ft and their weight varies between 43 tons and 63 tons. Placing most of the beams can be safely accomplished with the largest crane in Dallas. As seen in Figure 3-40, this is accomplished by locating the crane on the main lanes because it has the smallest radius. However, due to the cross street bridges over the highway eventually the crane will back its self into a corner where it can not physically place the beams from the main lanes as seen in Figure 3-41. In this case, the crane must move to the frontage road to place the remaining beams, as seen in Figure 3-42. Placing beams from the frontage road creates a larger radius than compared to when the crane is located on the main lanes. The weight and radius of several of the scenarios where the crane is located on the frontage road makes the clearances from abutments very close as seen in Figure 3-43. Another issue is that placing the beams requires the side of the highway where the beams are being placed to be shut down. When the crane is on the main lanes, this is not a major issue as the frontage road is still available for traffic. However, when the crane is placed on the frontage road both the frontage road and main lanes for the same direction of traffic must be closed, creating a large amount of traffic congestion.

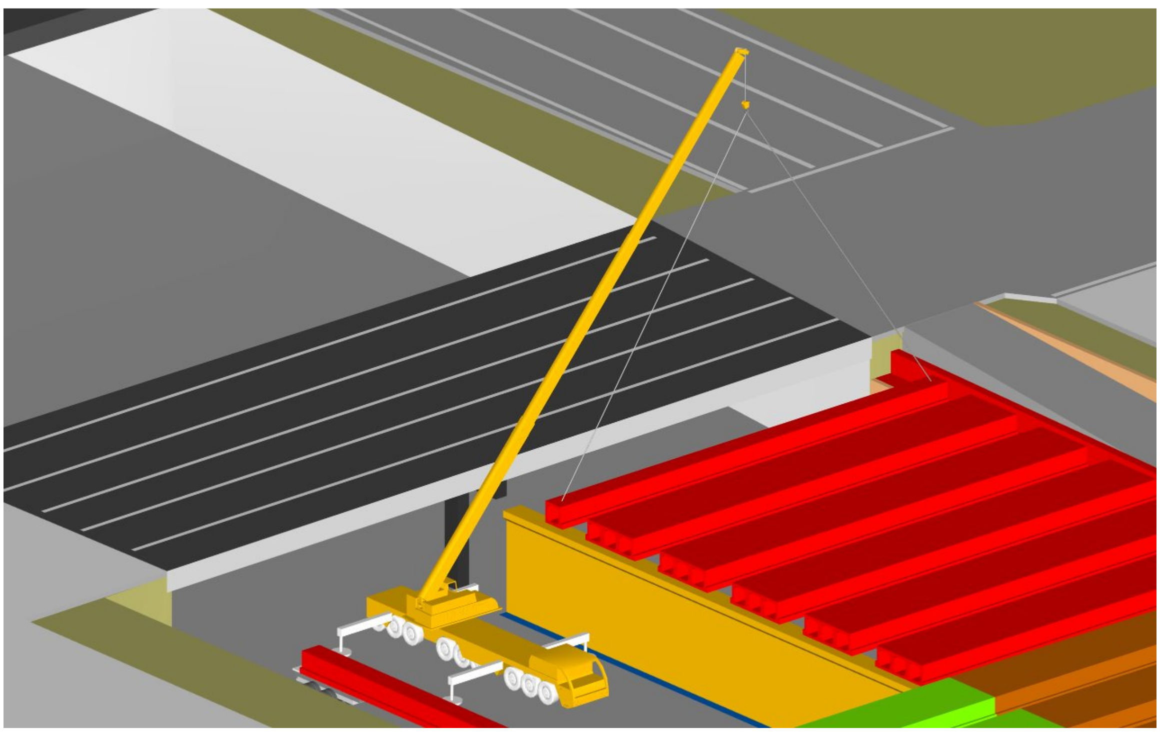

Figure 3-40 Crane Placing Beam from Main Lanes

Placing the beams from the main lanes is the most ideal scenario because it creates the smallest radius and only interrupts traffic on the main lanes, not the frontage roads.

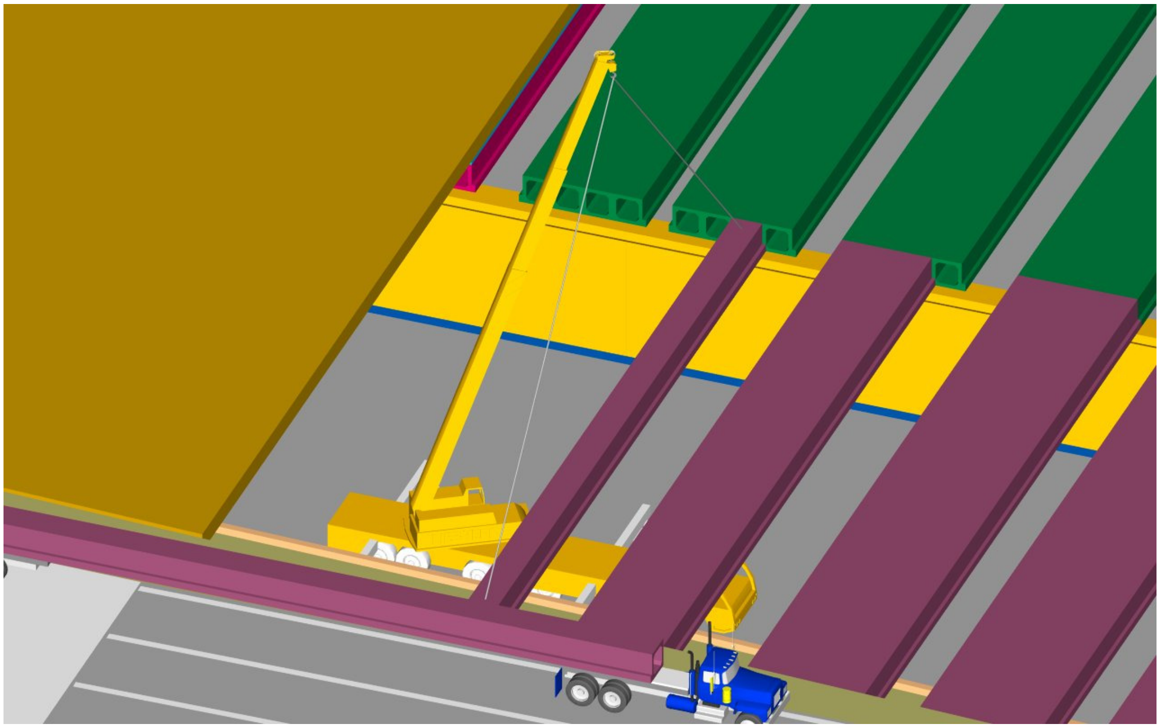

Figure 3-41 Crane Placing Beams from Main Lanes Backed Into a Corner

The crane will eventually be backed into a corner when placing beams on the main lanes. In order to place the remaining beams the crane must move to the frontage road.

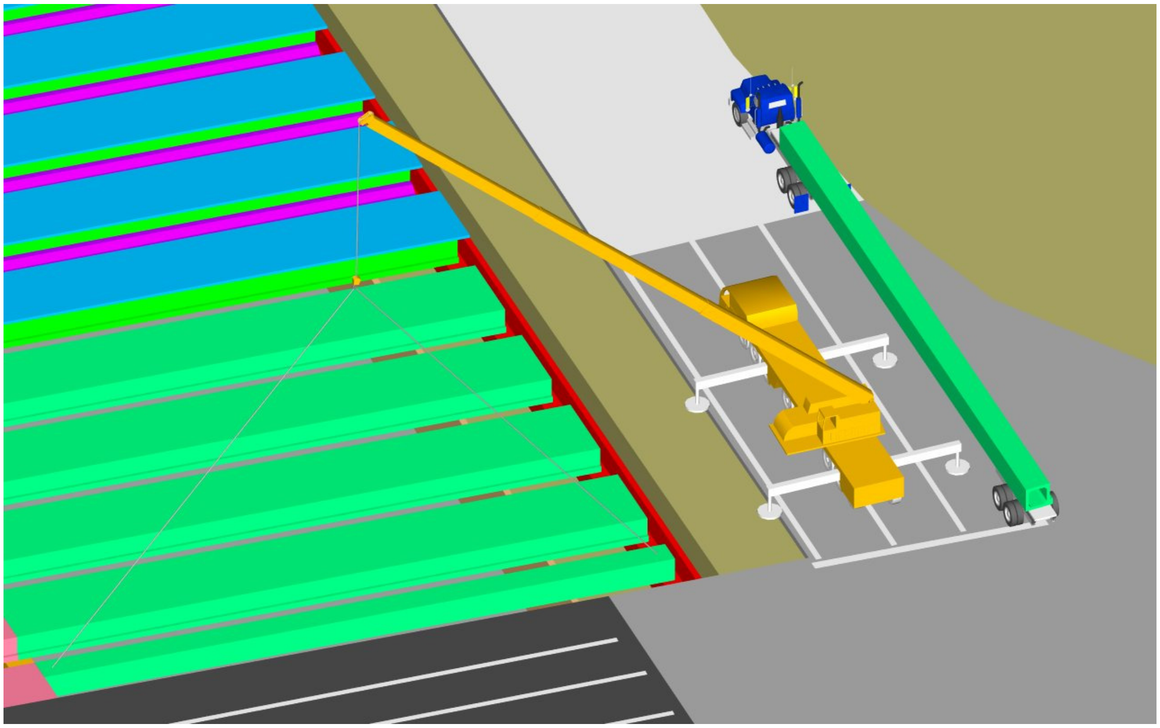

Figure 3-42 Crane Placing Beam from Frontage Road

Locating the crane on the frontage road creates a larger radius compared to when it is located on the main lanes. This large radius causes potential issues because of the large weight of the beams. Also traffic must be shut down on the frontage road and main lanes for the same direction when the crane is located on the frontage road, leading to congestion.

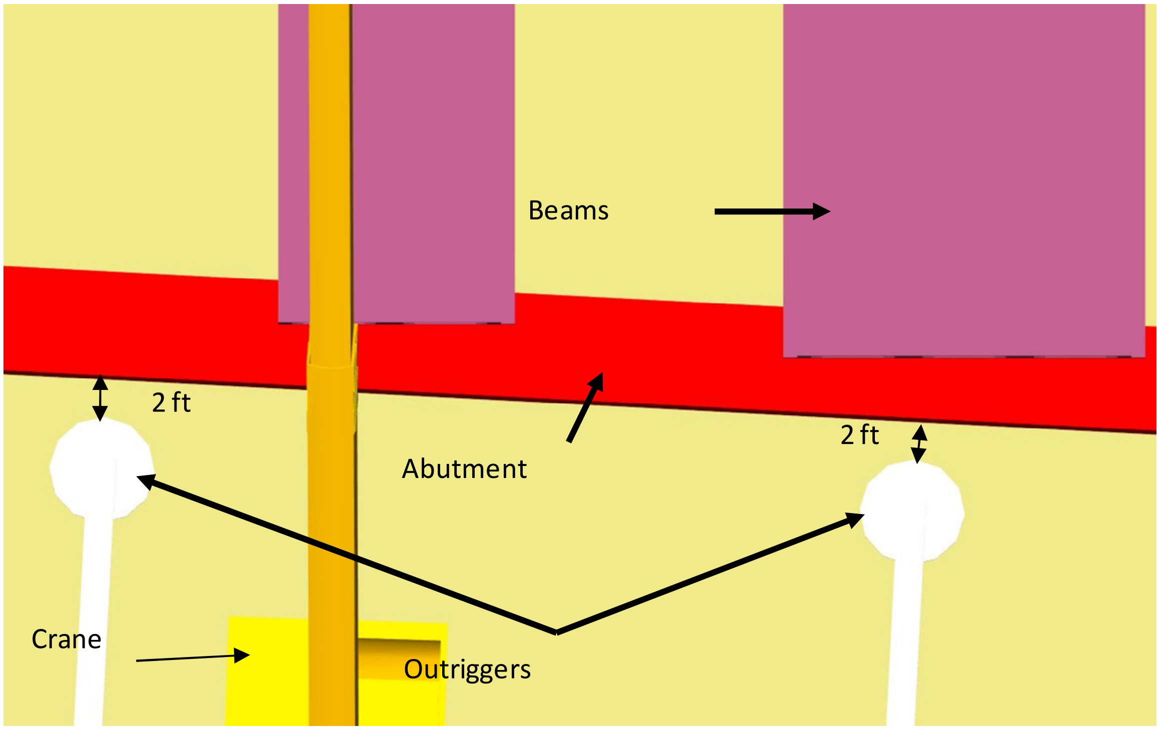

Figure 3-43 Close Clearance between Crane Outriggers (White) and Abutment (Red)

Crane outriggers are on earthy area between frontage road and abutments. The distance between the crane outriggers (white) and the abutment (red) in this beam placement scenario is only 2 feet. The crane (yellow) used is the biggest crane in Dallas. Beams are shown in purple. (plan view)

3.2.4.3 Tunnel Requirements

The Federal Highway Administration (FHWA) specifies that 800 ft of continuous covered road is considered a tunnel, and therefore must have life safety systems (as listed above in scope section) in order to accommodate vehicle traffic. The complete project covers 1,200 ft. Due to this requirement designers had to stage construction of the deck into smaller sections (<800 ft.) that must be totally complete, including all life safety systems. The sequence of construction for these individual sections had to be coordinated so that there was never more than 800 ft of road covered without life safety systems. Having to sectionalize the project forced a less than optimum construction sequence as well as created more work for designers to compartmentalize life safety system into sections so each section can function on its own.

3.2.4.4 Utility Bridges

The existing utility bridges are at the same elevation as the new pre-stressed box beams, but the utility bridges are not designed to support the load of the park. Therefore they must be demolished and their contents relocated to trench panels near the same area as the existing utility bridges. Also, the two utility bridges that cross the highway carry important communication lines for a client in Dallas, so extra care must be taken when transferring the utilities so there are minimal interruptions to service. The removal of utility bridges is a predecessor for completing the deck in the two areas west of the utility bridges' location, which is a great deal of work. This means in order to ensure the project is complete in time the utility bridges must be removed by a specific date. However, because the contents of the bridges must be relocated to trench panels there is a great deal of work to get the panels in place, specifically placing the beams in that area. That area is in the middle of the west set of beams as seen in Figure 3-44. If beam placement starts in the middle of the west span it will create two areas where the crane is backed into a corner, because the contractor will have to work from the middle toward the outsides, as seen in Figure 3-45. This issue creates a tradeoff between placing the beams in a sequence that minimizes the areas where the crane is backed into a corner and having the beams and trench panels up in time to relocated the utilities and demolish the bridges.

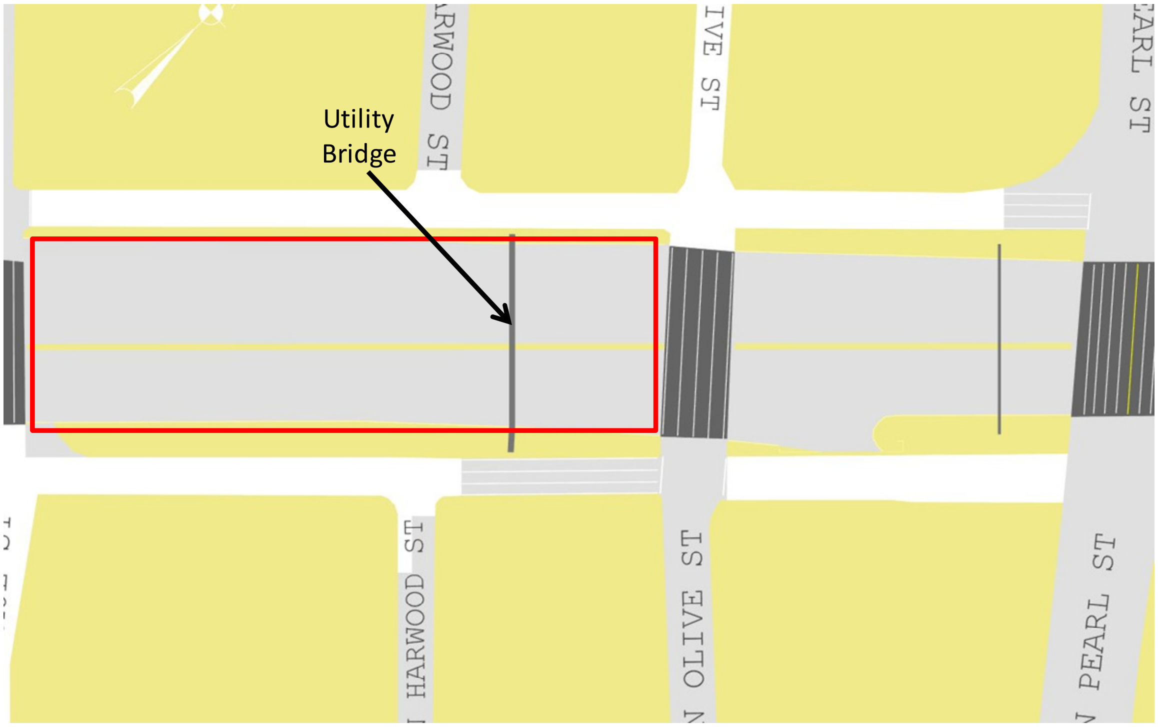

Figure 3-44 Utility Bridge Located In The Middle Of the West Set of Beams

The west set of beams (outlined in red) has a utility bridge (gray line) that is to be demolished in the middle of the set. Placing the beams in this middle area first, so the utilities can be transferred to trench panels will cause two areas (east end and west end) where the crane is backed into a corner.

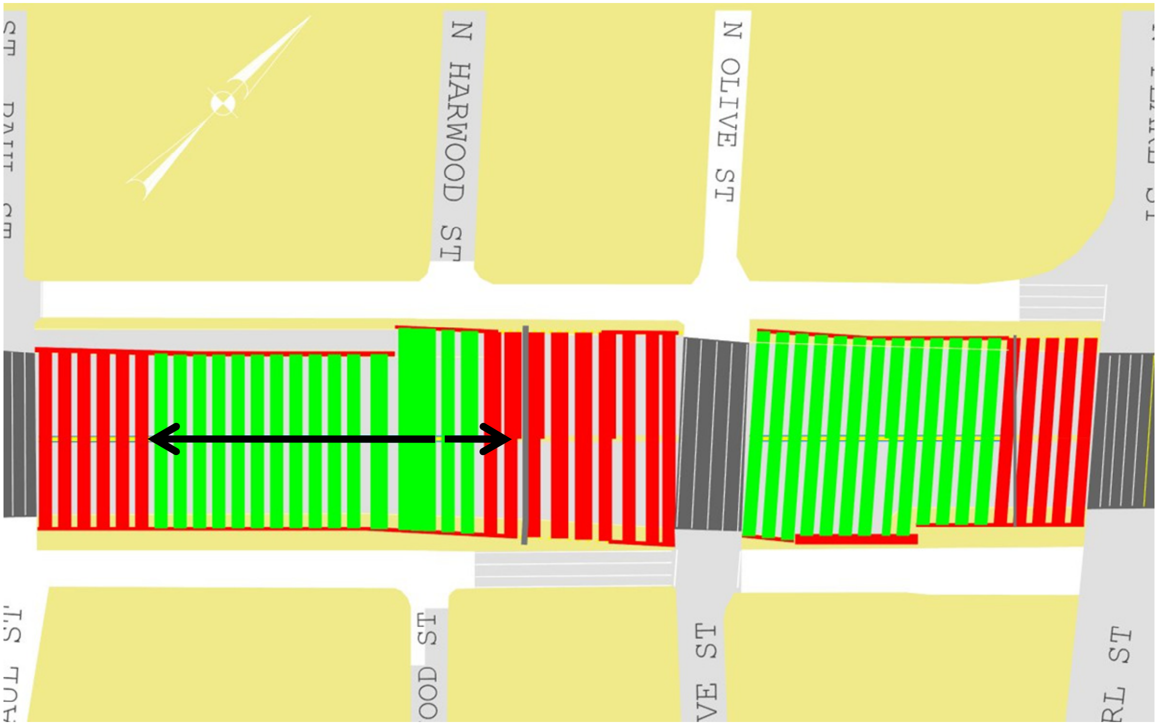

Figure 3-45 Areas Where Crane Will be Backed Into a Corner

There are three areas where the crane will be backed into corner (red), due to the cross street bridges. This happens when starting beam placement at the center of the west set because they will have to work toward the ends of the west set, rather than from one end to another as indicated by the arrows.

3.2.5 Analysis

In order to address some of these challenges discussed in the previous section, Gau conducted analysis during the construction phase as well as some of the pre-construction phase. This author has continued that support to TxDOT throughout the construction phase. Gau (2009) document his work and findings from the previous two years.

Gau was directed by TxDOT in early 2008 to create a 3D model of the project. He eventually created a simple 4D model in addition. The original intent of the models were to show visual images and videos of construction due to the publicity of the project. The TxDOT Public Information Office (PIO) used the models to educate the public by putting them on their website. The colored 3D images were much more appealing than black and white 2D drawings and worked well with the rendered park images. The construction department had already seen the benefits of 3D and 4D models on another one of their projects - the eastern extension of the President George Bush Turnpike so they decided to use the models to support construction once it had started. The construction applications are presented below.

The 3D models Gau created were frequently used during meetings to communicate the nature of the project and specific topics involving TxDOT project team members. Several concerns were highlighted while visualizing model animations and navigating through the models. For example, a small utility bridge raised many questions between project members when it was in the foreground of the 3D model, whereas this utility bridge is difficult to perceive in the set of 2D plans.

Gau (2009) focused his analysis work on the beam placement issue discussed above. The issue had not been explored in much depth by the TxDOT at the time, but Gau identified the issue before the project was let by TxDOT. In order to demonstrate the difficulty of placing the beams to TxDOT, especially when backed into a corner, Gau created 3D and 4D models of the crane placing beams from both the main lanes and frontage road, as seen in Figure 3-46 and Figure 3-47. A kinematic analysis was also done to determine the size of crane needed. This initial analysis indicated a large enough crane would be difficult to find in Dallas.

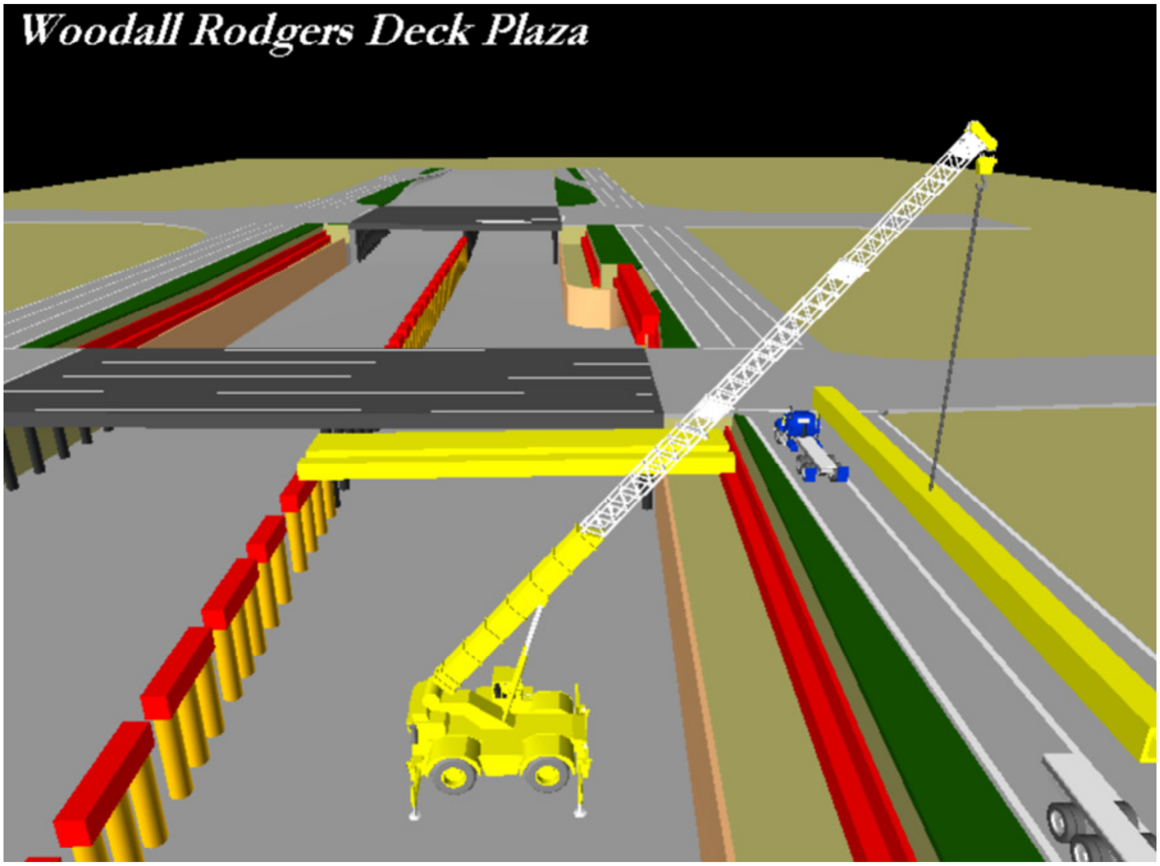

Figure 3-46 3D Model of a Crane Placing Beams Located On the Main Lanes.

This is the scenario that creates the smallest radius. Therefore it should be used as often as possible. Eventually the crane will back into corner as it approaches the cross street bridges and will not be able to work from the main lanes.

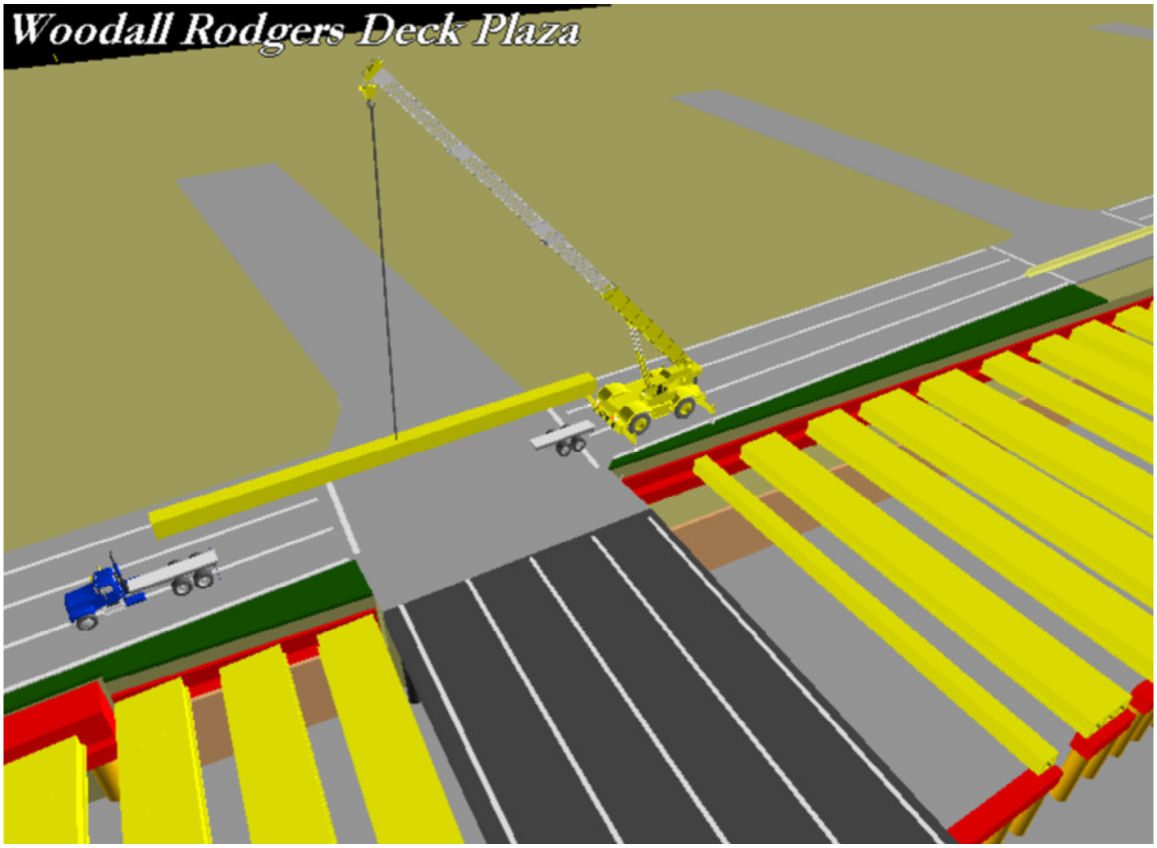

Figure 3-47 3D Model of a Crane Placing Beams Located On the Frontage Road

This is the scenario that creates the largest radius. It is necessary to place the crane on the frontage road when it is backed into a corner close to the cross street bridges. The radius and weight is so large in this scenario the availability of a crane large enough in the Dallas area is a concern.

The author of this thesis has continued to support TxDOT during the construction phase and has expanded the areas of support. This was accomplished by creating a complete 4D model that matched directly to the contractor's schedule (sequence, durations, scale of activities, etc.). Previously, Gau had created a simple 4D model by grouping similar elements (retaining walls, center wall, etc.) and animating them with all the same durations in a simple order (one at a time). This is similar to the photo construction sequence presented above. The model gave viewers an idea of the construction sequence, but not much analysis could be completed with it. The complete

4D model allowed the author to analyze the contractor's construction sequences as well as productivity.

The 4D modeling software used is very conducive to schedule updates. As long as the activities IDs have stayed the same, the software program can update the start and end dates of each activity for the entire project in less than 5 minutes. This author has utilized that advantage to update the Woodall 4D model with the monthly schedule update from the contractor. Updating the model allows this author to verify the contract is not working out of sequence. To date, no major issues have been found with the sequencing.

This author has also analyzed the contractor's productivity with the monthly schedule updates. For one schedule update the 4D animation of the schedule helped the author see that the amount of beams the contractor was planning on placing in the future was about twice as much as they had previously accomplished on the real project. This was easy to discover on the 4D animation because for the dates in the future a large amount of beams in a short amount of time appeared on the screen (indicating they were under construction), as compared to the amount of time the beams that had already been placed took to show up on the screen. After that visual anomaly in the 4D model, a more in-depth analysis of the schedule confirmed the large jump in productivity without any proposed changes (from previous work) about how to meet that productivity. The visualization of a large amount of information in the 4D model made this analysis and discovery fairly simple.

The author continued the beam placement analysis by creating more detailed 3D models of specific beam placement situations using the specific crane the contractor selected. The beams the contractor set first did not have any issues because the beams were in the middle of the west set. For that situation the crane and beam truck could be located on the main lanes. Therefore, no analysis was requested by the author. TxDOT asked for the author's assistance when situations where the crane would be in areas with less clearance started taking place. The first issue was checking the clearance of a proposed crane location near the eastern utility bridge, as seen in Figure 3-48. Through 3D analysis with the model and 2D geometry, the author determined the crane boom would clear the utility bridge. However the amount of clearance was small so it was important for the crane to be parked precisely in the spot the author used for the analysis.

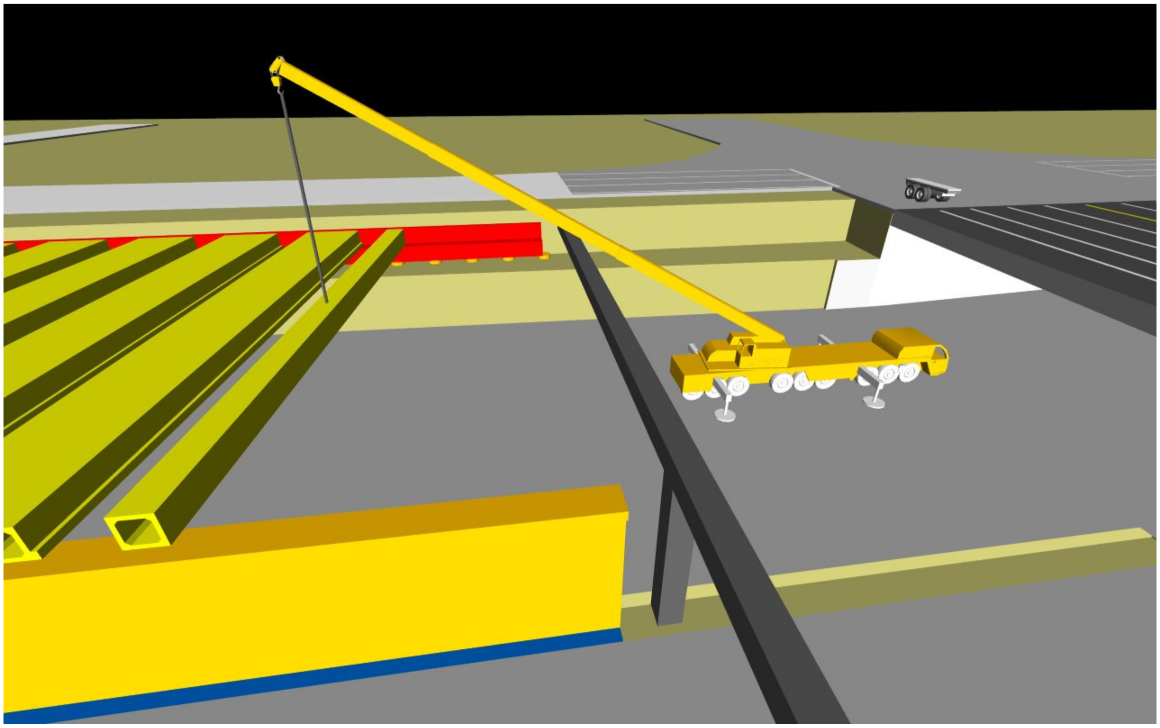

Figure 3-48 Checking the Clearance of the Crane in a Tight Area

The model provided a visual check that the amount of clearance between the crane boom and the utility bridge was small, so the crane placement had to be very precise when setting beams from this position.

After completing the clearance check, TxDOT asked the author to develop several 3D models of potential crane locations for the areas where the crane would be backed into a corner. Those areas are illustrated in Figure 3-45. The author used the crane technical manual (load charts, crane dimensions, etc.) as well as the construction documents and the 3D model to determine the location of the crane for the different areas. The load charts and construction plans allowed for precise calculation and measurement as a check to the 3D model; while the 3D model was valuable to visualize the impacts of the different scenarios. The 3D model was also very valuable at presenting the issues to TxDOT. The author developed models for both spans (north and south) for all three areas of concern for a total of 6 models. Many of the areas resulted in the same scenario (crane located on frontage road) so only the 4 different types of scenarios are presented here. For easy identification of areas the author has numbered the areas 1-6. Those numbers can be seen in Figure 3-49 and will be used to discuss the different scenarios developed. For all of the proposed scenrios that author took into consideration the safety for the traveling public and workers, the impact to traffic, and the complication to execute. For area 1 the crane was able to be located on opposite side main lanes, as seen in Figure 3-50, because the beams were small enough for that radius and beams were not in place on the opposite side. Area 2 had to have the crane located on the frontage road, as seen in Figure 3-51, because there was no other space. Beams had already been placced in area 1. For areas 3 and 4 the crane is not large enough to place the beams from the frontage at the end near the bridge. Those beams are the largest on the entire project. Therefore, the crane will have to start placing the beams from the main lanes at the bridege and work east, as seen in Figure 3-52, until the crane is backed into beams already placed near the middle of the set, as seen in Figure 3-53. The remaining beams will need to placed from the frontage road, as seen in Figure 3-54. Those beams are smaller than the largest ones directly next to the bridge and therefore can be placed from the frontage road with the crane, although with a very small clearance as illustrated in Figure 3-43. Areas 5 and 6 will both have to have the crane located on the frontage road because there is not enough clearance for the beams and crane to be located on the opposite side as was done for area 1. The beams are too long to be lifted from the main lanes because of the beams that are already placed and the cross street bridge as seen in Figure 3-55. To place beams from the oppoiste side the beams and crane must be located on the opposite side or the radius is too large.

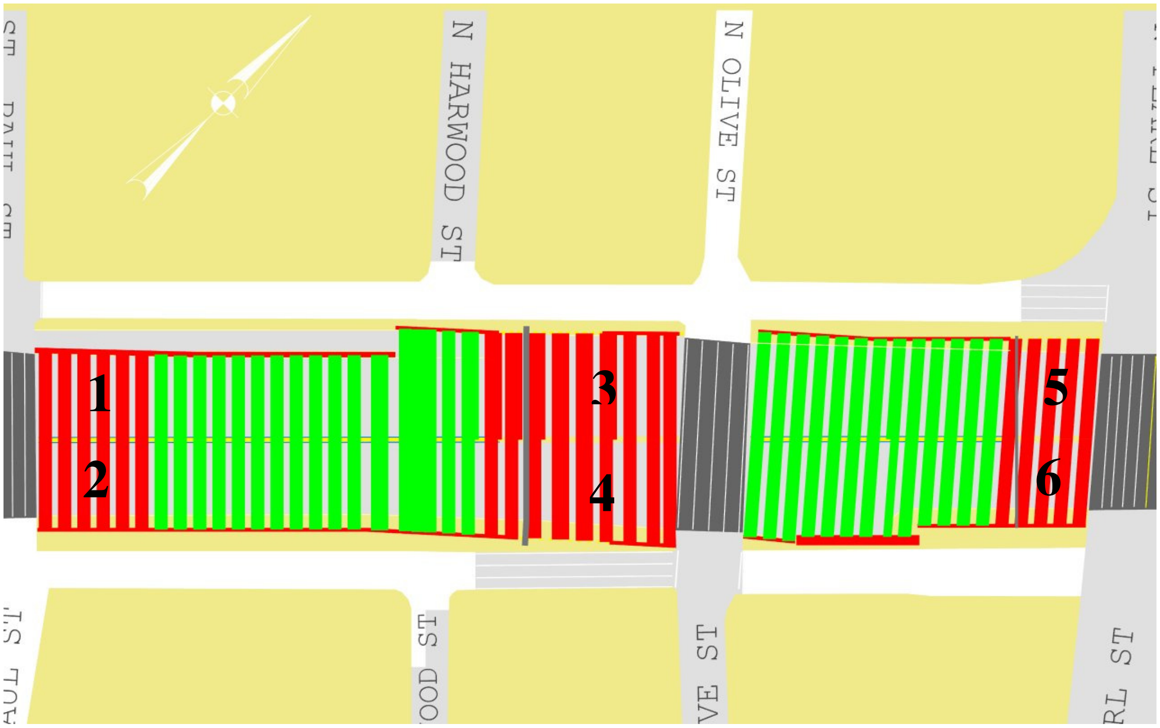

Figure 3-49 Identification of Areas Where Scenarios Were Modeled for TxDOT

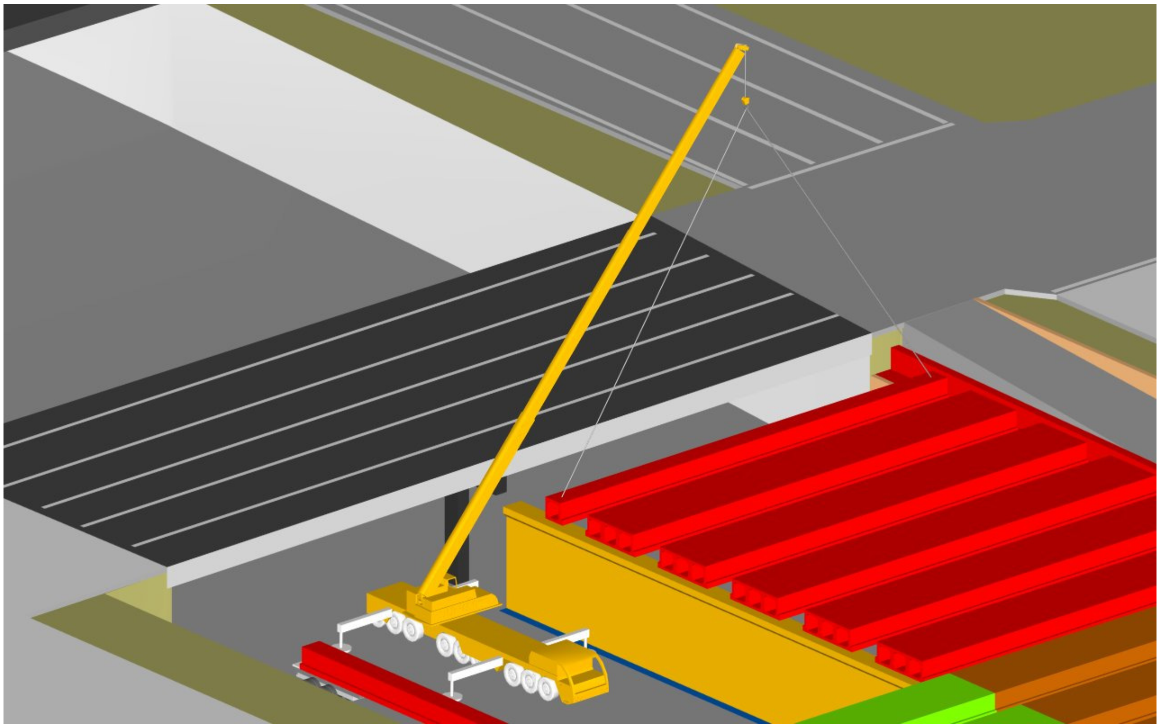

Figure 3-50 Beam Placement from Opposite Side Main Lanes.

This scenario was created for area 1. It is approximately the same radius as locating the crane on the frontage road. However, the frontage road does not have to be shut down for the crane. Clearance of the boom and center wall needs to be checked.

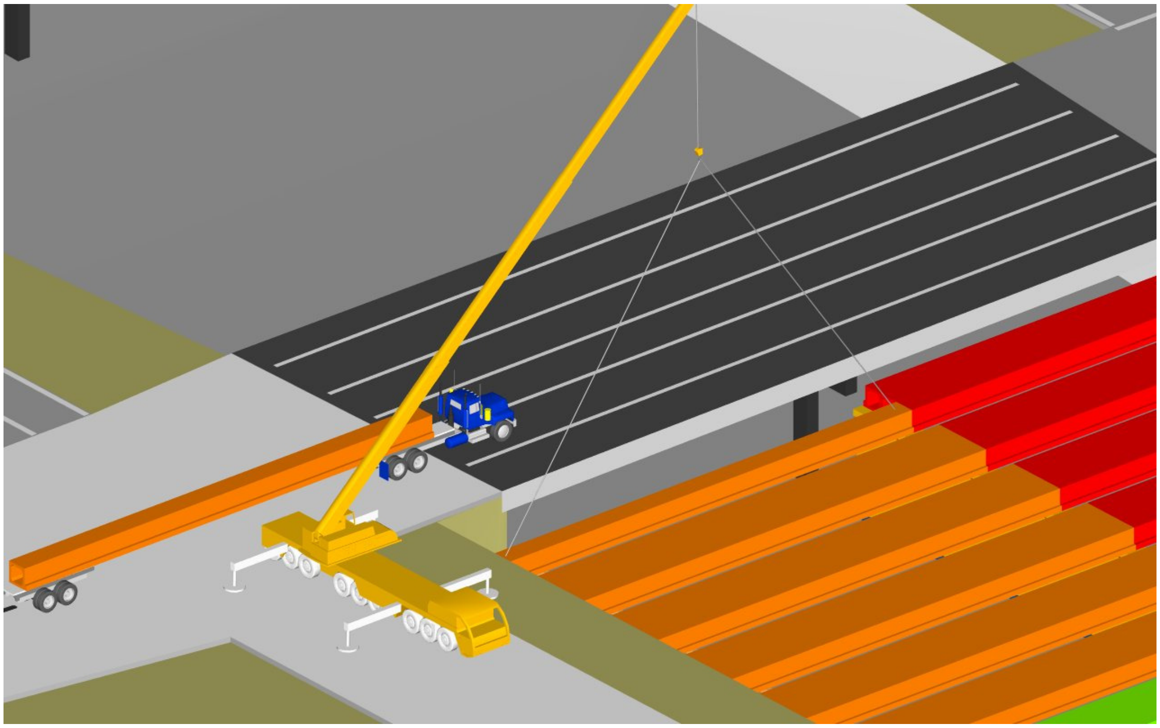

Figure 3-51 Beam Placement from Frontage Road

This scenario is area 2. It creates a larger radius than the crane placed on the main lanes, but is necessary when backed into a corner. The crane location was determined by using the longest radius that could support the beam weight with the most amount of counterweight added to the crane. In this scenario the outriggers were located off the frontage road approximately 15 feet from the drop off. Soil stability needed to be checked.

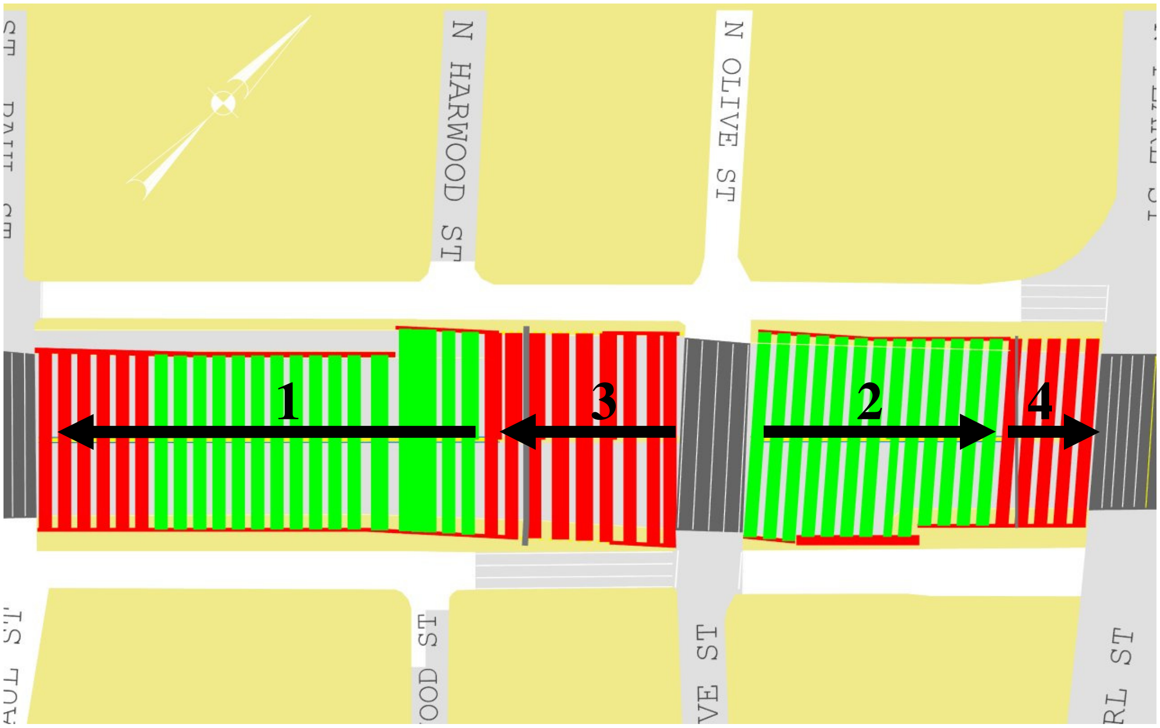

Figure 3-52 Order and Direction of Beam Placement by Contractor

The contractor will start beam placement in the middle of the west set and work toward the west. After that the contractor will place beam on the east set starting on the west side and work toward the east until they encounter the utility bridge. After the utility bridges are demolished the contractor will place the remaining beams on the west set starting at the Olive St. Bridge because the beams near the bridge are the largest on the site and can only be placed with the crane on the main lanes (creates smallest radius of all scenarios). Finally the contractor will place the remaining beams for the east set. All of those beams are approximately the same so the contractor can work toward the Pearl St. Bridge.

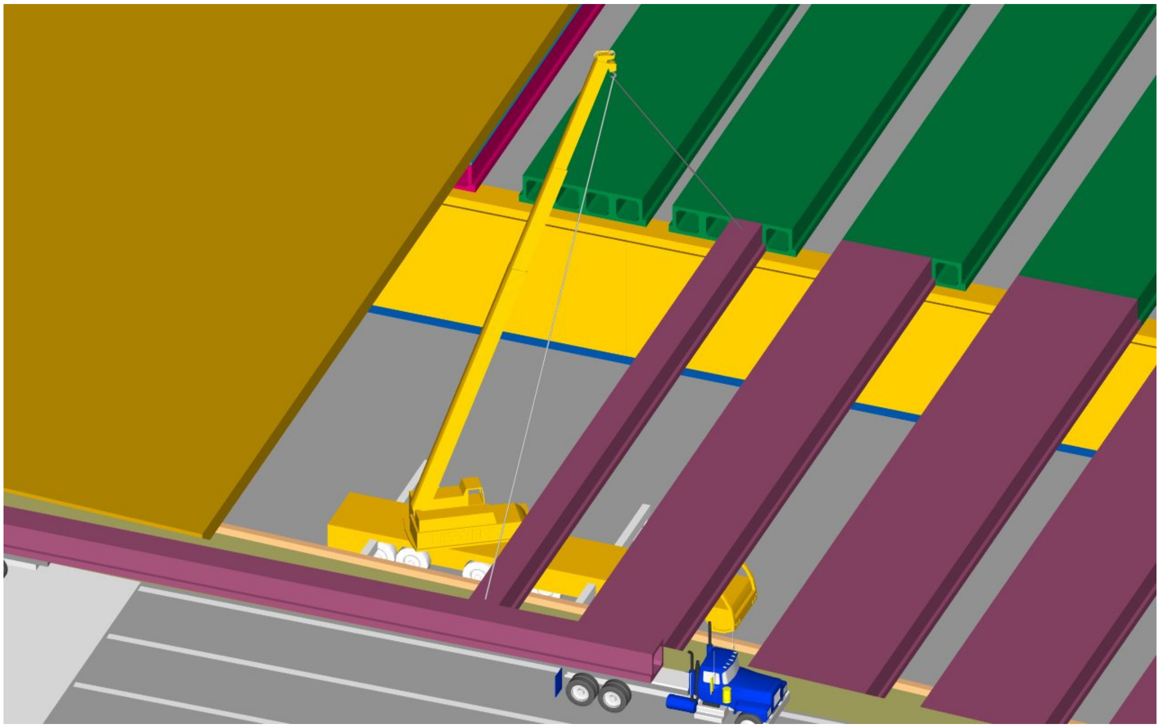

Figure 3-53 Crane Backed Into Other Beams on Main Lanes

This scenario is for area 3. The beams directly next to the cross street bridge are too large to place the crane on the frontage road. Therefore, the crane has to start on the main lanes at the bridge and work east until it is backed into the beams previously placed. This is because the beams near the east end are smaller, but very close to the capacity of the crane. Therefore, the crane must place as many beams as possible from the main lanes, before moving to the frontage road. There were several obstacles that influenced this crane location. The height and length of the counter weights for the tail swing clearance, the boom length needed to pick the beam from the frontage road, and the smallest radius that boom length could accommodate all needed to be considered. The 3D model helped identify a few of these issues as well as provide a visual check of the initial issue identified by the author.

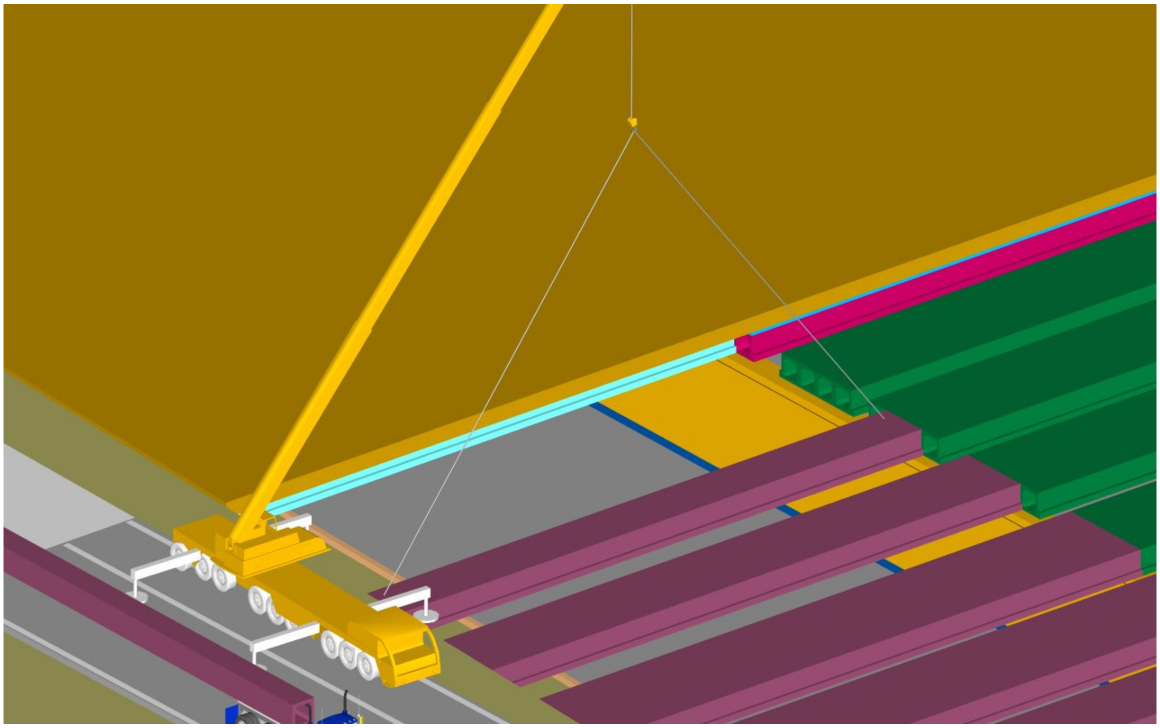

Figure 3-54 Crane Placing Beams from Frontage Road near Already Placed Beams

Once the crane runs out of room to place beams from the main lanes, it must place them from the frontage road. This scenario is possible because the beams closer to the middle of the set are smaller than the ones near the bridge which were too large to place from the frontage road. There is still a very small clearance for this situation of about 2ft between the crane outriggers and the abutment as seen in Figure 3-43

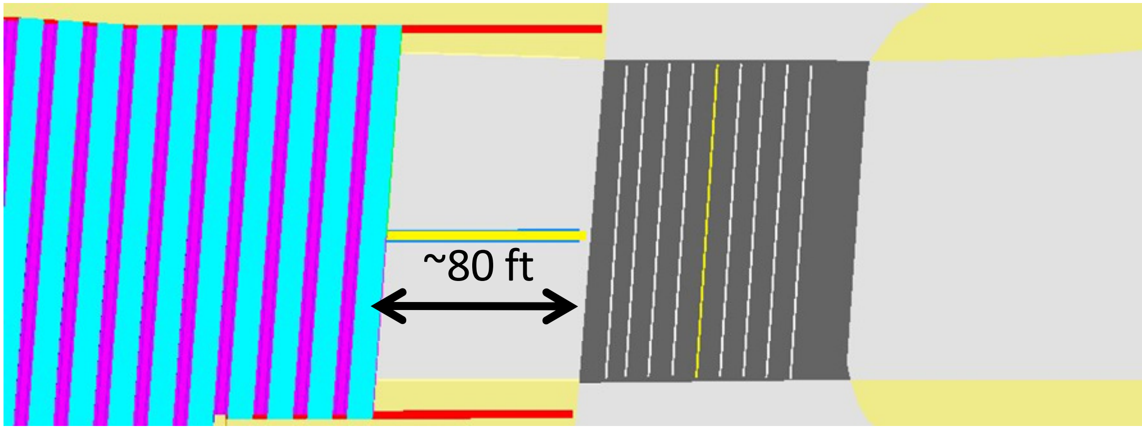

Figure 3-55 Clearance Between Cross Street Bridge and Beams Already in Place

For areas 5 and 6, the clearance to lift the beams through the opening between the cross street bridge and beams already in place is ~80 ft, while the beams to be placed are ~90 ft. This means the crane cannot not be located on the opposite side of main lanes because the beam truck also has to be located on the same main lanes or the radius is too large for the crane.

Gau and this author have supported the construction team with 3D and 4D analysis when issues came up. Ideally though, the issues would never have happened. Assisting the construction team on this project for the past two years with the work presented above has lead this author to believe that utilizing 3D and 4D visualization during the planning and design phases could have prevented these issues from happening, or at least given the designers a better chance to catch the errors before construction started. This claim is supported by the overwhelming amount of research that supports using constructability early in the planning process and continuing during all project phases, which was discussed in Chapter 2. Along with the issues presented above, this author has interviewed the TxDOT project manager about additional issues they have encountered on this project and their impacts. With the analysis from the previous two years of work that was presented above and the knowledge gained from the literature review, the author has developed specific ideas about how 3D and 4D visualization could be used throughout the entire design phase and could have improved the issues that have come up during construction of this project. For the issues discussed below, each one has a detailed description as well the impact(s) the issue had on the project. For the proposed solutions the author presents how the literature has impacted this category of issue and then builds on the literature by adding the experience he has gained from the previous two years of work on this project. Also included is a scale for how much impact 3D and 4D modeling could have for the project. The scale is based on a combination of the impact the issue has on the project and the impact 3D/4D has on the issue. A **Large Impact** indicates the issue is significant and that 3D/4D could have a significant impact on the issue. A **Medium Impact** could be a combination of a large issue and small impact of 3D/4D on that issue, or vice versa, or both the issue and 3D/4D impact on that issue are medium. An **Indirect Impact** means the issue has a significant impact on the project, but the cause of the issue was related to construction; not design. Therefore, 3D/4D in the early design phase could not have prevented the issue, but using the 3D/4D developed during design can reduce the impact. Finally a **Potential Issue** is an issue that has not had a significant impact, but the conditions are ripe for it and that 3D/4D in the early design phase could have potentially prevented it. All of the issues are summarized at the end in table x for easy review.

3.2.6 Issues

There are two main issues for this project that drive other issues. One of them is that the lane closure restrictions are severely limiting. The other is that due to the complexity of the project, there is not an established "best way" to complete the work. The limiting restrictions further complicate the work.

3.2.6.1 Limiting Restrictions

As discussed above, the project is located in downtown Dallas. Therefore, in order to ensure there is adequate flow of traffic the designers restricted when lane and exit ramp closures could take place. For example, the Pearl St. exit ramp could not be closed during the State Fair of Texas because that exit is the main exit for the fair. Another example is that all four of the main lanes of traffic can only be closed on the weekends, but not during the main shopping season between Thanksgiving and Christmas day. These types of restrictions are common for urban projects. However, the designers went a step further and also set a limit on the total amount of hours all four main lanes can be closed without having to pay lane rental fees as seen in Table 3-2. Because all four lanes must be closed to place the 315 beams, limiting the total number of free hours indicates how productive the contractor will have to be when placing beams. Even if there is not an event scheduled for a weekend, the contractor will have to pay to close the highway for beam placement if they have run out of free hours. From the analysis completed for TxDOT, the complications of placing the beams did not seem fully understood by the designer. The restrictions have contributed to the contractor working out of sequence; thus lowering productivity, and impacting traffic.

Table 3-2 Lane Closure Restriction and Hourly Rates (State Spur 366 Plans, 2009)

No. of Lanes Closed	Time Period A	Time Period B	Time Period C		Time Period D	
	Hourly Rate	Hourly Rate	Hourly Rate	Free Lane Closure Hours	Hourly Rate	Free Lane Closure Hours
1	$4,500	$1,000	$0	n/a	$0	n/a
2	$9,500	$8,000	$0	n/a	$0	n/a
3	$16,000	$14,000	$5,000	0	$1,000	0
4	$32,000	$20,000	$8,000	158	$2,200	336

The total number of hours all of the main lanes can be closed without incurring lane rental charges is limited to 336 for Time Period D and 158 for Time Period C. This restriction goes one step further than simply dictating when and number of lanes can be closed. This dictates the productivity the contractor must meet for placing beams, as all the main lanes must be closed when placing beams.

The main topic for this issue is the need for a more realistic way to analyze the project. According to Liapi et al. (2003) "3-D modeling, as a graphical representation methods, is closer to the representation of the physical reality of a structure than 2D plans, and can, in principal, provide a better understanding of the aspects of a project that depend on spatial constraints". Manrique et al. (2007) modeled tilt-up panel erection in 3D before any operation at the construction site and the models "helped to understand the installation sequence and helped to modify it according to space constraints. All of these authors discuss 3D and 4D being closer to reality which allows for issues not initially thought about to become clear.

This author believes the difficulty of the project should lend the designers to put more thought into the restrictions they specify. The design team could have simulated both overall construction sequencing and specific complicated activities in a 4D model. The overall 4D model would help to look at the overall beam placement sequence including how to group them for the small amount of available work time during a weekend. The activity 3D simulation would allow the design team to realistically see the difficulties of placing the beams. 3D and 4D models are able to synthesize a large amount of information so designers can visualize the work needed to complete the project in a format closer to real life; thus providing more information and better information to make design decisions. 3D/4D could have made a **Large Impact.**

3.2.6.2 How to Complete Work

The challenges discussed in a previous section make it difficult to establish a "best way" to complete the work, especially because many of the challenges interface with other challenges (not isolated issues). For example, the utility bridges are linked to beam placement because the bridges cannot be demolished until the trench panels are in place which requires the beams to be in place. The project also utilized unique components. The first 53 beams fabricated were rejected because very large pre-cast box beams have never been built in Texas. There are several other indicators that support the claim that there is not a "best way" to complete work. The TxDOT field project manager got the sense that the designers thought most of the work would happen at night with a large shut down between thanksgiving and new years due to holiday traffic. This was because when he was assigned to the project he was told he would not have much to do during that time, and could work on other projects in the area. This however is not how the contractor is completing the work. According the project manager, "they [contractor] are working all the time, and taking advantage of every free lane hour possible". Also the TxDOT project manager commented that "every contractor would have done the work a different way". Further evidence that there is not a "best way" to complete work is the large variances in the bids. There was a small difference between 1st and 2nd place, but difference between 2nd and 3rd place bid was ~12%. This indicates very different interpretation of the difficulty of the project. Also, all the bids the contractors submitted were higher than the engineering estimate which indicates the designers did not really have a good idea about the difficulty of executing the design. To compare this project to a project that utilized 3D/4D, all estimates in the Paradise Pier project were within 3% of each other and 2.5% of the estimate (Ago et al., 2005).

This issue deals with the need to analyze construction sequences in order to find the best method, and then communicating it to the potential bidders. Monique et al., (2007) discovered one of the biggest benefits of 3D and 4D modeling is simulating projects in advance. Manrique et al., (2007) also mentions another benefit of 3D modeling is reducing uncertainty of construction operations. Simulation could have reduced uncertainty and improved the construction process. The work that was completed with 3D and 4D models then needs to be communicated to potential bidders. To do that, Gao et al. (2005) looked at a case where they used the 4D model the design team created as part of the bid package. This was done to visualize problematic design areas or construction sequences. That way, potential bidders were better able to fully understand the design and construction work. This resulted in bids closer in proximity to each other with fewer contingencies.

The design team could have used 3D and 4D models to analyze different construction sequences just as they did for making the restriction more realistic. But the designers would have also derived great benefit while creating the 3D and 4D models. Building the models forces planners and designers to think about how all the different parts of the project integrate and interface with each other and how they will be built. This is because all the elements that were designed separately are integrated in a 3D model. Once the model was complete, the design team could have used it to analyze different construction sequences in order to find the most optimum one as well as identify areas of concern. The areas of concern could have been discusses with a constructability consultant to develop the best solution. Once the areas of concerned were identified they could have been communicated to the potential bidders. 3D/4D could have a **Large Impact.**

3.2.6.3 Fabrication

The engineer of record initially designed the box beams with draped tendons after consulting with several fabricators to make sure the beams could be fabricated with draped tendons. However, the fabricator the contractor selected was not one of the fabricators the engineer consulted. Beams with draped tendons create large upward forces which require tie-downs at 1/3 points with a significant amount of reinforcement. The continuously changing lengths of the beams make the 1/3 points different for each beam. Because of this, the fabricator was going to have to build a new casting bed which in turn would have made the price of the beams with draped tendons very high. Straight tendons do not require the additional reinforcement at the 1/3 points so they are easier to cast, and thus less expensive to fabricate, but also more complicated to design. The contractor requested a re-design to straight tendons, but the engineer of record required $130,000 for the re-design. The contractor and engineer argued for several weeks about the cost until the contractor finally paid for the re-design. The time to re-design the beams and arguing about the costs delayed the fabrication of the beams. The delay of the fabrication forced the contractor to reconfigure the beam placement sequence. The new sequence made placement of some beams more difficult. TxDOT's project manager believes 6 -8 weeks of schedule delay can be attributed to the fabrication issue.

This issue deals with the need to visualize information, specifically the schedule. Koo and Fischer, (2000) found that as a visualization tool, 3D and 4D models "obviate the need to conceptualize the association between components and activities to comprehend the schedule. Songer et al. (2001b) concluded that "the quality of a schedule, both in terms of correctness and goodness, is dramatically improved when the scheduler has access to a 3-D design representation". "Goodness" meaning better workflow. The improvement is because "as the scheduler's spatial comprehension of the design is improved, the scheduler can devote more resources to creating a quality schedule". This was particularly true for complex configurations. 3D allows better visualization of the schedule.

For this fabrication issue, changes in the planning and the design phase would not have made an impact. But if the contractor had a better idea of how much impact the delay was going to have they might have tried to expedite the fabrication/re-design process. The 3D and 4D model that was created during the design phase could have been given to the contractor so they could visually see the impact the delay was causing. The contractor could have updated the model with the new schedules they created, just as this author has done with the monthly update schedule. The 4D model would have been a visual way of seeing the impact of the fabrication issue on the rest of the project that needed to be complete. Nothing in the design phase would have changed, but the 3D/4D model that was created during the design phase could also benefit the contractor. 3D/4D could have an **Indirect Impact.**

3.2.6.4 Missing TCP Phase

For different parts of construction, traffic must be shifted both inward and outward depending on what part of the project is being worked on. For the center wall traffic is shifted outward, and the lane closest to the center is closed for safety of the workers. For the retaining walls and abutments traffic is shifted inward and the outer most lane is closed for safety reasons. Ideally, traffic would only be shifted each way (outward and inward) once, but because there are utility bridges present, this is not the case. The center bent wall cannot be complete until the utility bridges are demolished, as seen in Figure 3-56. The utility bridges cannot be demolished until the trench panels are in place and the utilities are relocated. The trench panels require the beams to be placed which requires the center wall and abutments to be constructed. Therefore, traffic is first shifted outward to build most of the center wall. Then, traffic is shifted inward to build all of the retaining walls and abutments. Then beams and trench panels can be placed and utilities transferred to the trench panels, and the utility bridges demolished. After the utility bridges are demolished the remaining center wall can be built, which will require the traffic to be shifted back outward, as seen in Figure 3-57. However, the TCP does not include that second shift outward for the remaining center bent wall. The TxDOT project manager noticed the missing phase when reviewing the plans prior to construction. To resolve the issue they are returning to the previous TCP phase where the center bent was constructed. This will add costs for moving barriers, striping, etc. TxDOT does not think there will be a significant schedule impact.

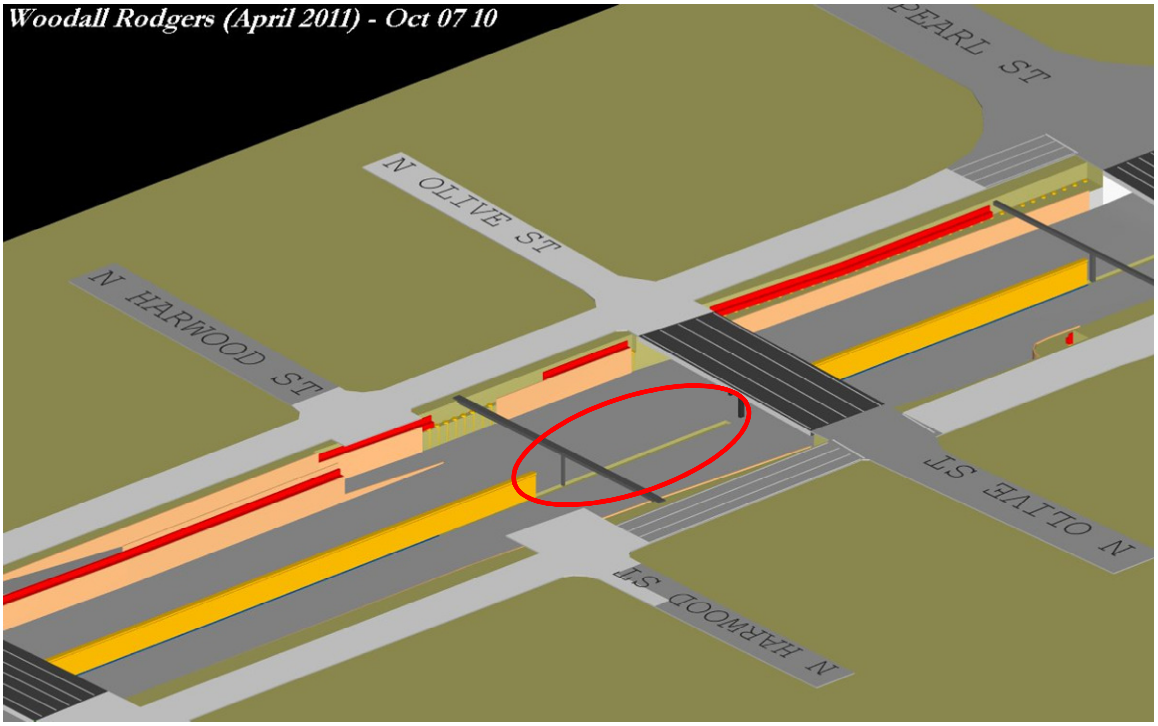

Figure 3-56 Center Wall Segments Excluding Area of Utility Bridges (red circle)

The center wall cannot be built in the area where the utility bridges are located. The utility bridges must be demolished, but before that, the abutments and retaining wall must be built so beams and trench panels can be placed. The utilities will then be transferred to the trench panels and bridges demolished.

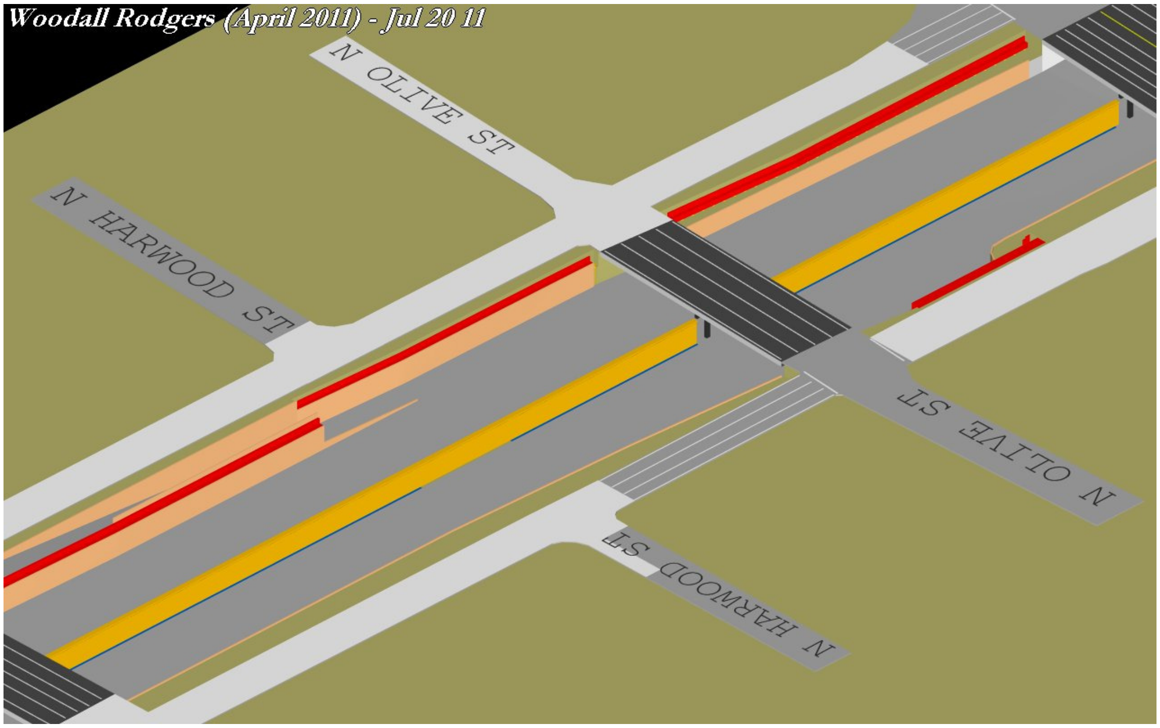

Figure 3-57 Center Wall with All Segments Completed

The center wall has been completed after the utility bridges have been demolished (beams not shown for clarity)

This TCP issue deals with the need to visualize the work space as well as traffic control planning. Koo and Fisher (2000) found that 3D and 4D models show the spatial constraints between components, enabling users to detect space-related conflicts" They also found 4D CAD could be used to "detect potential site logistical challenges and accessibility problems" (Koo and Fischer, 2000). The 4D model they created help them identify a scheduling issue. The proposed schedule had one set of stairs installed early to allow access to the 2nd floor. However, when access was needed to the stairs other work was going on that limited access. The second set of stairs was not scheduled to be complete until after the work blocking the first set of stairs was clear. This meant there was a possible delay to work on the 2nd floor. For this case study, the easy visualization of space in a 4D model was what lead to the discovery of the issue. For projects specific to transportation Liapi (2003) found "construction phasing of highway interchange projects is directly related to traffic planning and therefore is of critical importance that the animation of the construction process also displays traffic planning measures.

The 2D plans of this project do not present the fact that the utility bridges are one of the key issues for the completion of the project. There are no plan sheets specific to the removal of the utility bridges, and on the sheets that mention the bridges, it is fairly hard to tell what impact it has on new construction. The new construction sheets only mentioned that is will be removed, not how it will be removed. Removal is usually considered an easier part of construction phasing, and thus not a lot of thought is put into it. A 3D model could have shown the spatial impact the utility bridge has on the center bent wall as it is not very obvious in the 2D plans. With the synthesis of information the 3D model could have provided, the design team would have a better chance of realizing the sequence of constructing the center bent. If the 3D model would not have helped, the 4D model created at a later date would have also provided a better opportunity (as compared to 2D plan review) to catch the error. The 4D model would most likely be used to review different TCPs. The 4D model Liapi (2003) created that took into account traffic phasing and construction sequencing would have provided the most information to the design team. 3D/4D could have a **Medium Impact.**

3.2.6.5 Beam Placement Sequencing

The design sequence for placing the beams creates three areas where the crane is backed into the cross street bridges (Figure 3-45) which makes placing the beams much more difficult. There are three areas because for the west set of beams, the design specifies beams placement start in the middle of the span and work toward the outsides, as seen in Figure 3-58. The contractor actually planned to start at the west end and work toward the east (eliminating one area where the crane is backed into a corner), but delay due to fabrication made the contractor re-sequence work. Starting beam placement in the middle is what is specified in the plans so now the contractor is actually following the design specifications. For the areas where the crane is backed into the cross street bridges, the crane must be located on the frontage road which creates a longer radius and the frontage road being shut down as seen in Figure 3-51. This method requires a larger crane, sometimes 2 cranes, and additional planning required for the more difficult lifts. All of those impacts add costs.

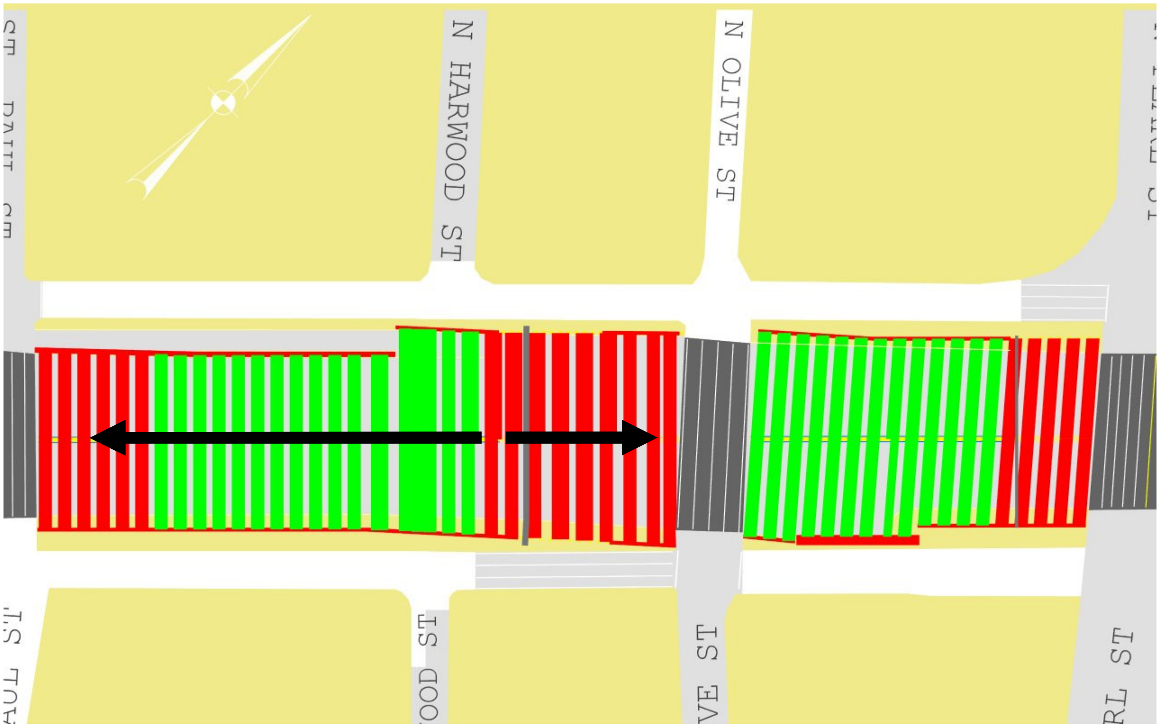

Figure 3-58 Areas Where Crane is Backed Into Corner (Shown In Red)

Beam placement for the west set starts in the middle and works towards the edges, thus creating two areas where the crane is backed into a corner for the west set.

For large crane lifts past research supports the use of 3D simulation. For a project with complex tilt wall construction Manrique et al. (2007) modeled decisions in 3D before any operation at the construction site, which "helped to understand the installation sequence and helped to modify it according to space constraints. Kim et al. (2011) studied the Cheongpoong Grand cable-stayed bridge where construction engineers involved in the project had a concern when the edge girders were moved from the trailer to the installation site they would collide with the pylon. When viewing the continuous-event simulation they found that "the location of the derrick crane and the sequential order of the construction tasks had to be changed" or there would have been a collision.

The 3D simulations this author has already created, as seen in Figure 3-51 to support construction could have helped the planners and designers understand the complexities of such large lifts, especially in the areas when backed into the cross street bridges. With this additional information the designers might have chosen to re-sequence beam placement so there were only two areas where beams were backed into cross street bridges. Also, the areas selected could have been the areas with smaller beams rather than the larger beams. 3D/4D could have a **Large Impact.**

3.2.6.6 Park Amenities Contractor

The contractor for the park finish out (restaurant, fountains, etc) will slightly overlap work with TxDOT's contractor. However, there is no contractual tie between the two contractors. Because of the interesting contractual obligations there could potentially be conficts. The park amenities contractor needs to be told their start date at least a month in advance, but currently every monthly schedule update from the TxDOT contractor delays the completion date for their scope of the work. The finish out contractor’s cost could be affected if they do not have enough notice from the TxDOT contractor on when they can start.

This issues deals with the integration of different parties on a project. In addition to coordinating different trades past research has found that owners can use 4D models to “determine the optimum contractual work packages…and phased handover” (Gao et al., 2005). On one of the cases Gao et al. (2005) studied, the owner “successfully used the 4D visualization to determine the contracting packages by visualizing the break-up of project scope into various contractual ‘chunks’ in the 3D model and by seeing progression of the ‘chunks’ over time in the 4D model” (Gao et al., 2005). For traffic literature, Liapi et al. (2003) had very productive meetings between contractors and engineers where several different schedule alternatives were created during the meetings and then displayed side by side for comparison. The two different parties were able to agree on a most preferred schedule during those meetings because the 4D model provided a platform where all the information could be seen at once.

There has not been an issue as of this writing, but there is the potential for one. The ability of a 3D and 4D to visualize a great deal of information could be helpful for communicating information between the parties. Recently the 3D/4D model of the project was used to quickly show the finish out contractor the progress of the project. Gao et al. (2005) described a case where 4D models were used to "determine the optimum contractual work packages…and phased handover to close the gaps as work was handed off from one party to another" on the Paradise Pier Disney project in Los Angeles. 3D and 4D could have a **Potential Impact.**

3.2.6.7 Park Utilities

The park features many amenities such as a restaurant, performance stage, water gardens, lights, drainage, lilly fountain, and restroom. These amenities require a significant amount of utilities (gas, drainage, water, electric, irrigation). There are also the utilities for the road (electrical, drainage) that need to be taken into consideration. All of those utilities are located in the trench panels. The large amount of utilities in the small amount of space creates potential issues. Someone on the project team requested a sheet with all the utilities displayed on it, but the sheet was unusable due to the intricacy of all the utilities. Also the McKinney Street car needed 2 -24" drilled shafts on each side of the highway (EB, WB), but the team has not been able to find a spot due to the congestion of utilities.

Utility conflicts are one of the most significant and frequent sources of construction delays on United States roadway projects (Chong et al. 2005; Ellis and Thomas 2002). As an indication regarding the frequency of utility conflicts, a report by the United States General Accounting Office (USGAO 1999) showed that 22 out of the 44 states surveyed in the research reported utility delays on at least 11% of the projects within their state.

3D is good for modeling utilities as they are underground, thus hard to see and check if there will be conflicts until there is one (hitting a line). A 3D check could be useful because so many different utilities are in such a tight area. **Potential Impact**.

Table 3-3 Summary of Issues for Woodall

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Limiting Restrictions	The restrictions were put in place to fulfill the need to keep traffic moving. However, the lane closure restrictions for beam placement are very limited.	**Large impact** - Simulating construction in a 4D model could have helped provide the designers with more realistic information regarding the difficulty of the project so they could specify more realistic restrictions. Manrique et al. (2007) modeled tilt-up panel erection in 3D before any operation at the construction site and the models "helped to understand the installation sequence and helped to modify it according to space constraints. The synthesis of information in a 3D model and even more in a 4D model helps visualize the work needed to complete the project in a format closer to real life. Thus providing more information and better information to make decisions from.	Synthesis of information	Simulations could be done as early on in the design phase as possible with "crude" models consisting of simple shapes and straight lines.
How to Complete Work	Pre-cast box beams have never been built in TX - Evidence: the first 53 beams fabricated were rejected. The designers did not seem to really know how work was to be completed. Each contractor approached project very differently - Evidence: large variances in the bids. There was a small difference between 1st and 2nd place, but difference between 2nd and 3rd place bid was ~12% thus indicating a very different interpretation of the difficulty of the project. Also, all the contractor bids were higher than the engineering estimate.	**Large impact** The design team could have used 4D models to analyze different construction sequences as well check productivity rates to make sure they were reasonable. 3D simulation models could have been used to simulate activities such as beam placement. Also building the 3D and 4D model forces planners and designers to think about how all the different parts of the project integrate and interface with each other. Koo and Fischer (2000 comment "when building the 4D model it encourages interaction between the designer, planner, and builder." Another important benefit is the communication of information. The resulting 3D and 4D model(s) could have then been used as part of the bidding phase to communicate the intricacy of the project to bidders.	Analyzing construction process, Communication of information	Simulations could be done as early as possible in the design phase with "crude" models consisting of simple shapes and straight lines. Productivity analysis accuracy would depend on the accuracy of the design, but "rough" numbers could be used early on. For the bidding phase a detailed model would be needed for bidders.

Table 3–3, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
How to Complete Work	Pre-cast box beams have never been built in TX or used for this type of project - Evidence: the first 53 beams fabricated were rejected. The designers did not seem to really know how work was to be completed. Each contractor approached project very differently - Evidence: large variances in the bids. There was a small difference between 1st and 2nd place, but difference between 2nd and 3rd place bid was ~12% thus indicating a very different interpretation of the difficulty of the project. Also, all the contractor bids were higher than the engineering estimate.	**Large impact** The design team could have used 4D models to analyze different construction sequences as well check productivity rates to make sure they were reasonable. 3D simulation models could have been used to simulate activities such as beam placement. Also building the 3D and 4D model forces planners and designers to think about how all the different parts of the project integrate and interface with each other how they will be built. Koo and Fischer (2000 comment "when building the 4D model it encourages interaction between the designer, planner, and builder." Another important benefit is the communication of information. The resulting 3D and 4D model(s) could have then been used as part of the bidding phase to communicate the intricacy of the project to bidders.	Analyzing construction process, Communication of information	Simulations could be done as early on in the design phase as possible with "crude" models consisting of simple shapes and straight lines. Productivity analysis accuracy would depend on the accuracy of the design, but "rough" numbers could be used early on. For the bidding phase a detailed model of "areas of concern" would be needed for bidders.
Fabrication	Fabrication of the box beams were delayed due to a re-design. The re-design was initiated by the contractor after the project was let in order to reduce the fabrication costs.	**Indirectly** - The 3D and 4D model that was created during the design phase could have been given to the contractor so they could visually see the impact the delay was causing. Nothing in the design phase would have changed, but the 3D/4D model that was created during the design phase could also benefit the contractor.	Visualization of schedule, Schedule analysis, Communication of information	Construction documents.

Table 3-3, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
TCP/Phasing	A phase of the TCP was left out of the plans. Traffic is shifted outward to built the center bent wall, excluding the segments where the utility bridges are. After the center bent wall is built (excluding utility bridge areas) traffic is shifted inward to build all the retaining wall and abutments. Once the utility bridges are demolished (after retaining walls and abutments are built) traffic needs to be shifted back outward to build the segments of the bent wall where the utility bridges were. However, the TCP does include the second shift outward	**Large impact** - A 3D model could have shown the spatial impact the utility bridge has on the center bent wall as it is not very obvious in the 2D plans. With the synthesis of information the 3D model could have provided the design team would have a better chance of realizing the sequence of constructing the center bent. If the 3D model would not have helped, the 4D model created at a later date would have also provided a better opportunity (as compared to 2D plan review) to catch the error. The 4D model would most likely be used to review different TCPs. The 4D model Liapi (2003) created that took into account traffic phasing and construction sequencing would have provided the most information to the design team.	Synthesis of information, Analyzing TCP, Increased spatial visualization with 3D	The utility bridges could have been model in detail from the beginning of the project as they were existing.

Table 3–3, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Beam Placement Sequencing	The design sequence for placing the beams creates 3 areas where the crane is backed into the cross street bridges which makes placing the beams much more difficult. This is because for one set of beams the design specifies placement start in the middle of the span and work toward the outsides. The contractor actually planned to start at one end and work toward the other, but delay due to fabrication made them re-sequence work so they are actually following the design specifications.	**Large impact** - 3D simulations of placing beams with a crane could have provided the design team with additional information about the difficulty of placing beams when backed into the cross street bridges. Kim et al. (2011) studied the Cheongpoong Grand cable-stayed bridge and when viewing the continuous-event simulation they found that "the location of the derrick crane and the sequential order of the construction tasks had to be changed" or there would have been a collision. The design could have been modified to re-sequence beam placement so there were only 2 areas where beams were backed into cross street bridges. Also, the areas with the smaller beams could have been specified rather than the larger beams.	Simulating potentially difficult and intricate construction operations, Reduced uncertainty	A low - medium level of detail is needed for the simulations. A lot of the important information (spans, concrete weight, crane sizes) is already known at the beginning of the project.

Table 3-3, cont.

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Beam Placement Sequencing	The design sequence for placing the beams creates 3 areas where the crane is backed into the cross street bridges which makes placing the beams much more difficult. This is because for one set of beams the design specifies placement start in the middle of the span and work toward the outsides. The contractor actually planned to start at one end and work toward the other, but delay due to fabrication made them re-sequence work so they are actually following the design specifications.	**Large impact** - 3D simulations of placing beams with a crane could have provided the design team with additional information about the difficulty of placing beams when backed into the cross street bridges. Kim et al. (2011) studied the Cheongpoong Grand cable-stayed bridge and when viewing the continuous-event simulation they found that “the location of the derrick crane and the sequential order of the construction tasks had to be changed” or there would have been a collision. The design could have been modified to re-sequence beam placement so there were only 2 areas where beams were backed into cross street bridges. Also, the areas with the smaller beams could have been specified rather than the larger beams.	Simulating potentially difficult and intricate construction operations, Reduced uncertainty	A low - medium level of detail is needed for the simulations. A lot of the important information (spans, concrete weight, crane sizes) is already known at the beginning of the project.
Park Amenities Contractor	The contractor for the park finish out (restaurant, fountains, etc) will slightly overlap work with TxDOT's contractor. However, there is no contractual tie between the two contractors. The finish out contractor needs to know a NTP date, but TxDOT's contractor keeps delaying work so the finish out contractor does not know when they will have access.	**Potential** - The ability of a 3D and 4D to visualize a great deal of information could be helpful for this issue. Recently the 3D/4D model of the project was used to quickly show the finish out contractor the progress of the project. Ago et al. (2005) and Hartmann et al. (2008) found that 4D models were used for determining contracting packages in the schematic design phase and for phased handover. Also the 4D model "coordinated the smooth process of handing over the preliminary site from the local department of public works to the owner's construction team before the deadline" (Ago et al., 2008)	Communication of information, Integration tool	Strategic work packages could be considered throughout the design process with an evolving 3D/4D model

Table 3-3, cont,

Issue	Description	How 3D/4D Could Help in Early Design Phase	Categories of 3D/4D Benefits	Level of Detail
Park Utilities	The park features many amenities such as a Restaurant, Performance stage, water gardens, lights, drainage, Lilly fountain, restroom. These amenities require a significant amount of utilities (gas, drainage, water, electric, irrigation). There are also the utilities for the road (electrical, drainage) that need to be taken into consideration. The large amount of utilities in the small amount of space creates potential issues.	**Potential** - 3D is good for modeling utilities as they are underground and thus hard to see and check if there will be conflicts until there is one (hitting a line) as Gau (2009) showed. Also with so many different utilities in such a tight area, there is more overlap and potential for clashes so a 3D check could be useful. There has not really been an issue or an issue with an impact to justify 3D modeling of utilities.	Synthesis of information, 3D spatial assessment	3D spatial impacts require fairly detailed model.

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

This author has been able to continue to support TxDOT on the projects they consider most important. These are the Woodall Rodgers Deck Plaza and the Eastern Extension of President George Bush Turnpike. This has been accomplished by updating the 4D model with the contractor's monthly schedule and further developing 3D and 4D models. Concrete benefits have been provided by analyzing the contractor's sequencing for errors and possible improvements and identifying a productivity issues. There was also a substantial amount of work done to highlight areas of concern for the beam placement methods. The 3D models not only helped complete the analysis, but were also very important to communicate the issues discovered.

From the work presented in this thesis, there are obviously benefits to utilizing this technology during construction. However, as the constructability review supports, the full benefits of construction knowledge can be best realized when implemented early in the planning process and continuing through the lifecycle of the project. The value of 3D and 4D visualization as a construction tool and overwhelming support for constructability to start early in a project creates an idea that visualization could have an even more impactful role if used in the early planning and design process. To investigate this claim, information taken from working on these projects for the past two years is supplemented with interviews of TxDOT staff to develop a list of issues for each project, as well as the impacts those issues have had on the project. For each of those issues a proposal of how using 3D and 4D visualization could help mitigate those issues when implemented during the early planning phases.

Most of the issues could have benefited from using 3D and 4D early in project planning phase. Issues that were caused by simple errors not caught during design review sessions, such as a missing phase of the Woodall Deck TCP, ROW acquisition schedule for PGBT, or demolishing the existing drainage before the new one was complete on PGBT, could have benefited from the synthesis of information in 3D and 4D models. They could also benefit from the experience of creating the models. All the individual components of a project are integrated together in a 3D model which forces planners to think about how all the elements will fit, work, and get constructed together. Other issues are not so simple that they are right or wrong. They are issues that were not optimized for construction, such as the beam placement sequencing for the Woodall Deck, or the traffic control plan and alignment selection for PGBT. These issues could have benefited from the ability to simulate construction with 4D models. The entire project can be analyzed by animating the 3D model with a schedule, or an important activity, such as use of a crane, can be analyzed with a 3D simulation. Other issues include ones that were not even thought to be an issue so they could be optimized, such as the limiting restrictions and difficulty of how to complete work on the Woodall Deck. Those issues could benefit from the synthesis of information just as the issues with simple errors, but also the ability these models have to facilitate meetings so large issues like these can be solved. Some of the issues could not directly benefit from using 3D and 4D early in the planning process. There are issues that come up that are specific to construction such as the fabrication issue for the Woodall Deck and the communications utility for PGBT. The 4D models that were created during the planning and design phase can be used by the contractor during the construction phase, just as the work discussed in this thesis. Therefore, the models created early in the project phase can indirectly be used to continue to solve problems. The final sets of issues are ones that are likely to become issues based on previous experience, such as the park amenities utilities and the park amenities contractor for the Woodall Deck. Utilities are an issue on several projects, and having two contractors overlap work can for sure cause some problems. For these issues the ability of the 3D and 4D models to facilitate meetings and communication is very beneficial. That way issues do not get out of hand. The work from the past two years and review of literature on the benefits of 3D and 4D visualization helped this author develop some very educated proposals for using the models in the early planning phases of the project.

4.2 Recommendations

3D and 4D visualization has been used since approximately the 1980s. Over the years a multitude of benefits have emerged. Based on the literature review completed by the author there is a great deal of research and proven benefits for buildings. So much that researchers are creating building information models that can be used for the life cycle of the building from early planning through decommission. In the last 10 years some of those same benefits for buildings have started to be researched and proved for transportation projects. By working on 3D and 4D visualization of transportation projects for the past two years this author has been able to produce solid benefits during the construction phase. In this thesis the author has used the information he learned to develop detailed proposals of how to use 3D and 4D visualization in the early planning phase to help eliminate some of the problems that come up in construction. The proposals have the background of two years of working on 3D and 4D models and an extensive literature review. The proposals are only a first step though for future researchers to implement the proposals and document if they work.

The natural next step to continuing this research is to implement 3D and 4D visualization early in the planning phases and use it until the project has been completed. The researcher would document how the models were used and the benefit they provided the planning and design team. The most convincing data would be quantitative, but this early in the research of the topic, qualitative is most likely. Completing this work would be a positive step to supporting 3D and 4D visualization for transportation projects, but also on a grander scale supporting the use of construction knowledge during the early planning phase.

Research should also continue to provide benefits of 3D and 4D during the construction phase as well. Qualitative benefits are becoming more proven, but quantitative information, similar to the data constructability research has proven, would make the argument for using 3D and 4D visualization for transportation much stronger.

Table 4-1 Summary of Areas of Potential Improvement for Both Case Studies

Category	Project	Issue	How 3D/4D Could Help in Early Design Phase
Construction Simulation	PGBT	Alignment Selection	**Large Impact** - The synthesis of information available in 3D and 4D models could have helped evaluate project tradeoffs early in the project development phase. More information would have been available, so hopefully the best (defined by project stakeholders) solution could have been implemented.
		Traffic Control Plan	**Medium Impact** - A 4D simulation of traffic and construction could have been used to analyze different versions of the TCP so the optimum one could be selected. This would have potentially allowed for lower bids on the project.
Synthesis of Information	PGBT	ROW Acquisition Schedule	**Small Impact** - 3D and 4D models could have been used to help with interface and coordination meetings throughout the design and planning process. The synthesis of information in one medium (3D/4D model) could present issues not thought to be present.
		Drainage Phasing	**Medium Impact** - The synthesis of information in a very visual way as well as the thought about how all the components of the project interact and the process in which they get built required when creating the 3D and 4D model gives the design team a better opportunity to catch this error as well as other similar errors.
	Woodall	TCP/Phasing	**Large impact** - A 3D model could have shown the spatial impact the utility bridge has on the center bent wall as it is not very obvious in the 2D plans. With the synthesis of information the 3D model could have provided the design team would have a better chance of realizing the sequence of constructing the center bent. If the 3D model would not have helped, the 4D model created at a later date would have also provided a better opportunity (as compared to 2D plan review) to catch the error. The 4D model would most likely be used to review different TCPs.

Table 4-1, cont.

Category	Project	Issue	How 3D/4D Could Help in Early Design Phase
Facilitate Meetings	Woodall	Limiting Restrictions	**Large impact** - Simulating construction in a 4D model could have helped provide the designers with more realistic information regarding the difficulty of the project so they could specify more realistic restrictions. The synthesis of information in a 3D model and even more in a 4D model helps visualize the work needed to complete the project in a format closer to real life.
		How to Complete Work	**Large impact** - The design team could have used 4D models to analyze different construction sequences as well check productivity rates to make sure they were reasonable. 3D simulation models could have been used to simulate activities such as beam placement. Also building the 3D and 4D model forces planners and designers to think about how all the different parts of the project integrate and interface with each other how they will be built. Another important benefit is the communication of information. The resulting 3D and 4D model(s) could have then been used as part of the bidding phase to communicate the intricacy of the project to bidders.
Construction Simulation	Woodall	Beam Placement Sequencing	**Large impact** - 3D simulations of placing beams with a crane could have provided the design team with additional information about the difficulty of placing beams when backed into the cross street bridges. The design could have been modified to re-sequence beam placement so there were only 2 areas where beams were backed into cross street bridges. Also, the areas with the smaller beams could have been specified rather than the larger beams.

Table 4-1, cont.

Category	Project	Issue	How 3D/4D Could Help in Early Design Phase
Communication	Woodall	Park Amenities Contractor	**Potential** - The ability of a 3D and 4D to visualize a great deal of information could be helpful for this issue. Recently the 3D/4D model of the project was used to quickly show the finish out contractor the progress of the project.
		Park Utilities	**Unsure** - 3D is good for modeling utilities as they are underground and thus hard to see and check if there will be conflicts until there is one (hitting a line) as Gau (2009) showed. Also with so many different utilities in such a tight area, there is more overlap and potential for clashes so a 3D check could be useful. There has not really been an issue or an issue with an impact to justify 3D modeling of utilities.
Indirect	Woodall	Fabrication	**Indirect Impact** - The 3D and 4D model that was created during the design phase could have been given to the contractor so they could visually see the impact the delay was causing. Nothing in the design phase would have changed, but the 3D/4D model that was created during the design phase could also benefit the contractor.
	PGBT	Communications Utility	**Indirect Impact** - The 3D and 4D models developed during the design phase could have been used while this issue was taking place to increase communication and help facilitate meetings, and evaluating different solutions.

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